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REVERSE OSMOSIS OF TREATED AND UNTREATED SECONDARY SEWAGE EFFLUENT

Doyle F. Boen, et al

Eastern Municipal Water District

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16. ABSTRACT

A pilot study was conducted to determine reverse osmosis feasibility on untreated and treated secondary effluents. Six commercially designed reverse osmosis pilot units, with 3,000 to 10,000 GPD nominal capacities and different module concepts, were tested. Post treatment of secondary effluent feeds, using alum clarification, sand filtration, granular activated carbon treatment, chlorine additions and pH adjustment, in different combinations improves reverse osmosis performance and significantly extends useful membrane life. Membrane fouling occurs despite post secondary effluent treatments. Enzymatic detergent solutions were moderately effective as membrane rejuvenation treatments. Inorganic fouling (particularly with phosphates) could be removed with solutions of the sodium salt of ethylenediaminetetraacetic acid. Of the module concepts tested, one of the tubular makes and the spiral wound had the best overall performance. Based on the pilot plant data, the total reverse osmosis costs, excluding brine disposal, is estimated to be \$0.78/1,000 gallons for a 0.9 MGD product water facility and about \$0.73/1,000 gallons for a 9 MGD product water facility.

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Grant No. WPRD 4-01-67
Project 17040 DSR
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NATIONAL ENVIRONMENTAL RESEARCH CENTER
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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in:

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

Reverse osmosis is one of the primary processes by which the environmental component of water may be protected from contamination. This text is an attempt to define some of the fundamental abilities, requirements and limitations of reverse osmosis when applied to various qualities of secondary sewage effluent.

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Director
National Environmental
Research Center, Cincinnati

ABSTRACT

A pilot study was conducted to determine reverse osmosis feasibility on untreated and treated secondary effluents. Six commercially designed reverse osmosis pilot units, with 3,000 to 10,000 GPD nominal capacities and different module concepts, were tested.

Post treatment of secondary effluent feeds, using alum clarification, sand filtration, granular activated carbon treatment, chlorine additions and pH adjustment, in different combinations improves reverse osmosis performance and significantly extends useful membrane life.

Membrane fouling occurs despite post secondary effluent treatments. Enzymatic detergent solutions were moderately effective as membrane rejuvenation treatments. Inorganic fouling (particularly with phosphates) could be removed with solutions of the sodium salt of ethylenediaminetetraacetic acid.

Of the module concepts tested, one of the tubular makes and the spiral wound had the best overall performance.

Based on the pilot plant data, the total reverse osmosis costs, excluding brine disposal is estimated to be $0.78/1,000 gallons for a 0.9 MGD product water facility and about $0.73/1,000 gallons for a 9 MGD product water facility.

This report was submitted in fulfillment of Project Grant Number 17040 DSR by the Eastern Municipal Water District, Hemet, California, under the partial sponsorship of the Environmental Protection Agency. Work was completed as of April, 1974.

CONTENTS

Page

Abstract iv

List of Figures vii

List of Tables ix

Acknowledgements xiii

Sections

I Conclusions 1

II Recommendations 3

III Introduction 5

IV Data Collection 9

V Computational Methods 15

VI Secondary Effluent 19

VII Post-Treatment of Secondary Effluent 24

VIII Reverse Osmosis Operations - Preliminary Discussion 46

IX Aerojet-General Corporation Reverse Osmosis Unit, Tubular Membrane Design 63

X American Standard (Abcor) Reverse Osmosis Unit, Tubular Membrane Design 78

XI E. I. Du Pont De Nemours & Co. Reverse Osmosis Unit, Hollow Fiber Concept 93

XII Gulf General Atomic Unit, Spirally Wound Module Design 114

XIII Raypak, Inc. Reverse Osmosis Unit, Modified Tubular Design 131

XIV Universal Water Corporation Reverse Osmosis Unit A Tubular Design 137

Contents Cont'd

No.		Page
XV	Inter-Unit Comparisons	160
XVI	Reverse Osmosis Costs	175
XVII	References	186
XVIII	Appendices	187

FIGURES

No.		Page
1	Aerial View of Facilities	20
2	E.M.W.D. Location Map	21
3	Post Secondary Effluent Treatment Facilities	25
4	Reactor-clarifier	26
5	Sand Filters and Activated Carbon Filters	27
6	Generalized Reverse Osmosis Unit Flow Scheme	47
7	Flow Schematic, 10,000 Gallon Per Day R.O. Unit	48
8	Microphotograph of Slime Removed from Universal R.O. Unit	53
9	Slime Microphotograph	53
10	Flow Pattern "a"	56
11	Aerojet-General Reverse Osmosis Unit	64
12	A vs. Time Plotted - Aerojet-General	75
13	A vs. Time Plotted - Aerojet-General	76
14	A vs. Time Plotted - Aerojet General	77
15	American Standard (Abcor) Reverse Osmosis Unit	79
16	Tubular Components, American Standard (Abcor) R.O. Unit	79
17	A vs. Time Plotted - American Standard	91
18	A vs. Time Plotted - American Standard	92
19	Du Pont Installation with B-5 Permeators in Place	93
20	14" Permasep® Pilot Plant Flow Diagram	95
21	Simplified Internal Flow Scheme, B-5 Module	97
22	Cut Away Drawing of Permasep® Permeator	97
23	A vs. Time Plotted - Du Pont	110

Figures Cont'd

No.		Page
24	A vs. Time Plotted - Du Pont	111
25	A vs. Time Plotted - Du Pont	112
26	Gulf General Atomic, Inc. Reverse Osmosis Unit	115
27	Details of Spiral Wound Module	117
28	A vs. Time Plotted - Gulf	129
29	A vs. Time Plotted - Gulf	130
30	A vs. Time Plotted - Raypak	136
31	Universal Water Corp. Reverse Osmosis Unit	138
32	Universal Reverse Osmosis Unit in Part	138
33	A vs. Time Plotted - Universal	155
34	A vs. Time Plotted - Universal	156
35	A vs. Time Plotted - Universal	157
36	A vs. Time Plotted - Universal	158

TABLES

No.		Page
1	Chronological Orientation of Experimental Program	8
2	Constituent Analysis Methods	12
3	Analytical Results of Seasonal Variation in Secondary Effluent	22
4	Domestic Water Quality to Sewered Areas of EMWD Compared to Secondary Effluent	23
5	Activated Carbon Physical Properties and Specifications	28
6	Post-Secondary Treatment Backflush Record	30
7 - 12	Post Secondary Treatment Unit Constituent Analyses	33-41
13	Post Treatment Data Weeks 16-33	42
14	Daily Computer Printout	50
15	Record of R.O. Unit Feed pH	52
16	Aerojet-General Reynolds Numbers	57
17	Estimated Minimum Reynolds Numbers per Modular Section	58
18	Program Output, "Water Permeability Studies"	59
19	Program Output, "Average Rejection Ratios"	60
20	Average Rejection Ratios Summary Output	62
21	Reverse Osmosis Process Information, Aerojet-General	66
22	Out-of-Service Record, Aerojet-General	67
23	Membrane Failure Record, Aerojet-General	68
24	Water Permeability Data, Aerojet-General	69
25	Aerojet-General Water Recovery Data	70
26	pH Adjusted Feed Water Quality, Aerojet-General	71
27	Product Water Quality, Aerojet-General	71
28	Brine Quality, Aerojet-General	72

Tables Cont'd

No.		Page
29	Water Recovery and Total Rejection Ratios, Aerojet-General	72
30	Average Rejection and Material Balance Ratios, Aerojet-General	73
31	Out-of-Service Record, American Standard	82
32	Reverse Osmosis Process Information, American Standard	83
33	Membrane Failure Tabulation, American Standard	84
34	Water Permeability Data, American Standard	85
35	Water Recovery Data Confidence Level, American Standard	86
36	pH Adjusted Feed Water Quality, American Standard	87
37	Product Water Quality, American Standard	87
38	Brine Quality, American Standard	88
39	Water Recovery and Total Rejection Ratios, American Standard	88
40	Membrane Cleansing History and Product Flux Increases, American Standard	89
41	Average Rejection and Material Balance Ratios, American Standard	90
42	Equipment Description, Du Pont Permasep® Package	96
43	Estimated Membrane Surface Area, Du Pont B-9's	98
44	Reverse Osmosis Process Information, Du Pont	100
45	Out-of-Service Record, Du Pont	101
46	Water Permeability Data, Du Pont	102
47	pH Adjusted Feed Water Quality, Du Pont	103
48	Product Water Quality, Du Pont	103
49	Brine Quality, Du Pont	104
50	Water Recovery and Total Rejection Ratios, Du Pont	104

Tables Cont'd

No.		Page
51	Du Pont Water Recovery Data	105
52	Constituent Data, Courtesy of Du Pont	105
53	Average Rejection and Material Balance Ratios, Du Pont	107
54	Membrane Rejuvenation Record, Du Pont B-5's	108
55	Membrane Rejuvenation Record, Du Pont B-9's	108
56	Membrane Rejuvenation Record, Du Pont B-9's	108
57	Du Pont B-9 Permeability Analyses, Colorado River Water Test Run	113
58	Out-of-Service Record, Gulf	118
59	Reverse Osmosis Process Information, Gulf	119
60	Gulf Water Recovery Data	120
61	Water Permeability Data, Gulf	121
62	pH Adjusted Feed Water Quality, Gulf	122
63	Product Water Recovery, Gulf	122
64	Brine Quality, Gulf	123
65	Water Recovery and Total Rejection Ratios, Gulf	123
66	Average Rejection and Material Balance Ratios, Gulf	125
67	Gulf Record of Membrane Rejuvenation	126
68	Reverse Osmosis Process Information, Raypak	132
69	Water Permeability Data, Raypak	132
70	pH Adjusted Feed Water Quality, Raypak	134
71	Product Water Quality, Raypak	134
72	Brine Quality, Raypak	134
73	Water Recovery and Total Rejection Ratios, Raypak	135

Tables Cont'd

No.		Page
74	Average Rejection and Material Balance Ratios, Raypak	135
75	Reverse Osmosis Membrane Performance Comparison, Universal vs Hemet Tests	140
76	Out-of-Service Record, Universal	142
77	Study of Life Spans, Membrane Sets, Universal	142
78	Process Information, Universal	143
79	Water Permeability Data, Universal	145
80	pH Adjusted Feed Water Quality, Universal	146
81	Product Water Quality, Universal	147
82	Brine Quality, Universal	148
83	Recovery and Total Rejection Ratios, Universal	149
84	Universal Water Recovery Data	150
85	Average Rejection and Material Balance Ratios, Universal	152
86	Membrane Rejuvenation Record, Universal	153
87	Maintenance and Allotment/100 Available Operating Hours	161
88 - 92	Operational Variables and Values	163-167
93	Comparison of Membrane Configurations	168
94	Average Per Cent Reductions of Constituents	170
95	Minimum Volume Increase Requirements per Unit to Meet Specific Demand - 10,000 gpd @ 90% Rejection	171
96	Estimate of Membrane Life Based on Product Water Recovery Loss	173

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Mr. Dean C. Rauscher - Reverse Osmosis Area
Mr. Richard K. Morton - Post-Secondary Treatment Area
Mr. Carson R. O'Dell - Chemist
Mr. Stephen A. Hays - Chemist (Author, Section A-6)

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SECTION I

CONCLUSIONS

1. The use of the reverse osmosis process in the Hemet, California, groundwater recycling program on treated or untreated secondary effluent feed is relatively expensive in comparison with importing Northern California low total dissolved solids water.

2. Effective post secondary treatment sequences (for the feed to the reverse osmosis process) are:

   (a) alum clarification followed by sand filtration,
   (b) sand filtration followed by granular activated carbon treatment,
   (c) though not directly tested, alum clarification followed by granular activated carbon treatment would also be an effective post secondary effluent treatment,
   (d) sand filtration alone was not as effective for post treating secondary effluents when compared to the prior listed post treatment sequences; however, sand filtration cost is considerably less and can be used as the post treatment on better quality secondary effluents.

   Each of the treatment sequences noted above is followed by chlorine addition (0.5 to 1.0 mg/l chlorine residual) and pH adjustment (5.0 to 5.5).

3. Reverse osmosis cost can be significantly reduced with post secondary effluent treatment and will significantly extend the useful membrane life.

4. The choice of post secondary effluent treatment depends on the quality of the secondary effluent and the reverse osmosis module concept. Closely packed (high density) reverse osmosis membrane surfaces are more subject to solids fouling than the open tube membrane configuration. Organics can be a significant factor in membrane fouling.

5. Despite the use of post secondary effluent treatments, reverse osmosis membrane fouling is a critical problem in reverse osmosis wastewater treatment. The most effective membrane rejuvenation treatments were:

   (a) Enzymatic detergent solutions
   (b) For inorganic fouling, particularly with phosphates, a solution of the sodium salt of Ethylenediaminetetraacetic acid.

6. The use of higher Reynolds number flow conditions, without excessive pressure drops, is an effective approach for retarding membrane fouling.

7. Of the module designs tested, the spiral wound and one of the tubular makes had the best overall performance.

8. The use of higher product water flux and lower solute rejection ("open") membranes is not appropriate even with the use of post secondary effluent treatments. This membrane type is subject to severe compaction, and internal membrane fouling which rapidly negates its initial advantages.

9. Based on the pilot plant data, taken at Hemet, California, the total reverse osmosis costs including post secondary effluent treatments and membrane rejuvenation, but excluding blending and brine disposal costs, are estimated at $0.78/1000 for 0.9 MGD product water and $0.73/1000 gallons for 9 MGD product water. These costs are based on 90% total dissolved solids rejection and up to 90% product water recovery.

10. Based on a secondary effluent average TDS of 716 mg/l, approximately 34% reverse osmosis product water can be mixed with 66% secondary effluent water to produce a blended water with 500 mg/l TDS. The cost for the R.O. product water portion is estimated at $0.25/1000 gallons for the 9 MGD facility.

SECTION II

RECOMMENDATIONS

The primary objective of this pilot plant study was to determine the feasibility of treating secondary effluent by reverse osmosis so that the final effluent might then be used advantageously as an integral part of the Hemet-San Jacinto closed basin ground water recycling program. Several types of small (under 10,000 gpd nominal capacity) reverse osmosis units were tested. Total costs for treating secondary effluent appear higher as compared to importing Northern California water. However, new developments in reverse osmosis are occurring so rapidly that some of the data and costs shown in this report may now be obsolete. It is recommended that reverse osmosis demonstration studies be conducted to determine the following:

(1) The cost tradeoff between the type of post secondary effluent treatment needed versus membrane life and membrane rejuvenations for 90 per cent product water recovery and 90 per cent salt rejection. The smaller reverse osmosis units used in this study showed a maximum of 75 per cent product water recovery on a once through use basis. The cost estimates based on this study data were projected to 90 per cent product water recovery.

(2) Additional experiences for determining operation costs are needed. For example, the manpower cost is about 20 per cent of the total reverse osmosis cost based on this study. This manpower cost is much greater than that suggested by the manufacturer for the spiral wound unit. This difference could be the result of interpreting manpower needs from a research and development study as compared to more routine operations.

(3) Brine disposal costs were not included because only small amounts of brine were generated. Also brine disposal was not an integral part of this study. However, brine disposal could be a very critical cost factor and could govern the type of post secondary effluent treatments employed, and the membrane replacements and membrane rejuvenations needed.

In a closed ground water basin area or for other effluent discharges, reverse osmosis would be used to control the total dissolved solids and other specific constituent concentrations in the final effluent. From a water management viewpoint, this control may be better accomplished by using the reverse osmosis process on the raw water (supply) side for the following reasons:

(1) Higher quality water would be available for domestic uses. Domestic users would share in the treatment costs, but also would benefit by not needing individual demineralizers which usually are more expensive to use. The wastewater would benefit because it would contain less total dissolved solids and other specific constituents (i.e., sodium) introduced by the regeneration of individual domestic units, thus avoiding extra buildup of salts which would be ultimately detrimental in a closed ground water basin or violate effluent discharge standards.

(2) Pretreatment of the raw water feed could be less costly as compared to secondary effluents prior to reverse osmosis treatment. For instance, organic fouling would be less likely by using a raw water feed.

Despite the apparent advantages cited above for treating raw water, it still may be necessary to use the reverse osmosis process on secondary effluent to avoid specific discharges and to meet the 1985 no pollutant discharge goal in the Federal Water Pollution Control Act Amendments of 1972. Therefore, side-by-side demonstration studies are recommended to determine the best cost effective use for the reverse osmosis process.

It is recommended that future reverse osmosis studies use a computer approach for compiling and analyzing data.

SECTION III

INTRODUCTION

Purpose of the Study

The primary objective of this pilot plant study was to determine the feasibility of treating secondary effluent by reverse osmosis so that the final effluent might then be used advantageously as an integral part of the Hemet-San Jacinto ground water recycling program. Reverse osmosis performance depends to a great extent on feed water quality. Particulate, colloidal, and dissolved substances in secondary effluent are known to have an adverse effect on reverse osmosis performance. Therefore, post secondary treatment processes were selected and operated under various combinations to determine their effectiveness for removing constituents that interfere with reverse osmosis performance. By conducting a study of post-secondary effluent processes, it was hoped that the most effective and economical process combination could be found.

Historical Record

By accepting responsibility for disposal of wastewater from the entire Hemet-San Jacinto Valley (a semi-arid region with an average rainfall of 12 inches and serving 30,000 people) Eastern Municipal Water District was thrust into an area of prime ecological importance. Almost simultaneous with the start-up of its water reclamation facility, EMWD launched a research project solely to study the effectiveness of its ground water recharge program. The saline condition of the reclaimed wastewater prompted the District to investigate current methods of salt removal. The need to eliminate salt from the recharge water is accentuated by local geological data indicating a closed underground water reservoir. Other than surface flow, little water is believed to escape the Valley. At the time this was fully realized, reverse osmosis was still in its early developmental stage, though it showed much promise in economical salt removal from saline waters. For this reason it was chosen for study by EMWD.

Assuming that reverse osmosis (R.O.) was economical and reliable, the role of R.O. in a wastewater recycling and ground recharge program would be the following:

(a) Reduce the concentration of total dissolved solids and refractories in the final sewage effluent;
(b) Curtail long-term concentration buildup of total dissolved solids and refractories in the ground water reservoir;
(c) Aid in maintaining the concentration of total dissolved solids and refractories in the ground water reservoir at levels acceptable to regulatory agencies;
(d) Minimize the future possibility of having to construct water treatment facilities (demineralization) that might be required at numerous locations over the ground water aquifer.

In December, 1966, the Federal Water Pollution Control Administration, now integrated into the Environmental Protection Agency, approved the proposal made by Eastern Municipal Water District of Hemet, California to undertake a Reverse Osmosis Demonstration Project under Research and Development Grant WPRD 4-01-67. The original title of the project was "Reverse Osmosis to Remove Dissolved Solids From Reclaimed Water Used in Ground Water Recharge Program" and the assigned contract number was WPRD 17040 DSR.

As of July, 1967, however, little research had been completed in the reverse osmosis field and its application to wastewater. A 15,000 GPD unit was operating at this time but had encountered numerous problems. It was apparent from these difficulties, that there were still some basic questions of Reverse Osmosis needing answers. Among these questions were, "What types of units are best suited for the various possible qualities of treated and untreated secondary effluent?" and "What are the economic advantages of using post-secondary treatment?" or even "To what degree can a fouled membrane/module be rejuvenated?" To the planners, the Hemet facility seemed well-suited to investigate these problems. Final plans and specifications received the approval of the Project Officer on September 11, 1968 and construction of the building and facilities was completed in December, 1969. Testing of the reverse osmosis units, was initiated on March 6, 1970, and concluded on June 25, 1971, a total operating period of 69 weeks.

Experimental Program

Originally, plans called for a study of one large reverse osmosis unit which was to operate on a feed of sand filtered secondary effluent. On the reasoning that more could be learned from a broader program, the plans were changed to include a study of five smaller units, each representing one of the major concepts of R.O. These concepts were: the flat plate design, the hollow fiber module, the spiral wound module, the high flux "loose" membrane tubular design, and the high rejection "tight" tubular design. (In the best interests of the study, a tubular design was substituted for the near-obsolete flat plate design.) In addition, a tubular design with the cellulose acetate membrane on the outside of the tube was also tested.

Under the revised objectives, post treatment of secondary effluent (feed) was expanded to include the following group of processes to be used in various combinations:

A. Reactor-clarification with alum and polymer coagulation

B. Pressure sand filtration

C. Granular activated carbon filtration

D. Diatomaceous earth filtration

E. Pre-R.O. unit chlorination (mandatory)

F. pH adjustment (mandatory)

(In subsequent references, capital letters as used above will be used to designate post-secondary treatment processes.)

For two major reasons it was also decided to increase the daily capacity of post-secondary effluent treatment equipment from 50,000 to 150,000 gallons:

(1) To allow for underdesign (manufacturers' stated unit capabilities were in terms of constituted salt solution, not wastewater).

(2) To allow for larger capabilities, should a magnified follow-on study take place, based on the assumption that the percent cost for a larger facility would be substantially below the per cent capacity increase.

Operating under the various controlled conditions, evaluation criteria were established based on total dissolved solids reduction observed for each unit. The scope of the evaluation criteria was eventually magnified to analyze each type of liquid flow for the maximum number of important constituents within the limitations of a two-man laboratory crew. The execution of these plans generated such a mass of data that it was necessary to sort and analyze the available information on an IBM 1130 Computer. This requirement was not anticipated in the planning of the original scope of the work.

Table 1 demonstrates how the above processes were integrated into the experimental program (capital letters designate the post-secondary treatment sequence).

Table 1. CHRONOLOGICAL ORIENTATION OF EXPERIMENTAL PROGRAM

Period Covered Week No.	Post-Treatment Sequence (A=Reactor-Clarifier) (B=Sand Filters) (C=Carbon Filters) (D=D.E. Filters) (E=Pre-R.O. Unit Chlorination) (F=pH Control)	Reverse Osmosis Manufacturer	Reverse Osmosis Type (T.P.'s - Turbulence Promotors)
2-7	A,B,C,E,F,	Aerojet	Tubular, Normal Flux
5-7	A,B,C,E,F	Du Pont	Hollow Fiber, B-5's
1-7	A,B,C,E,F	Gulf	Spiral Wound
1-7	A,B,C,E,F	Universal	Tubular, Normal Flux
7-17	A,B,C,D,E,F	Aerojet	Tubular, Normal Flux
14-28	A,B,C,D,E,F	American Standard	Tubular, W/T.P.'s
7-24	A,B,C,D,E,F	Du Pont	Hollow Fiber, B-5's
7-24	A,B,C,D,E,F	Gulf	Spiral Wound
7-30	A,B,C,D,E,F	Universal	Tubular, Normal Flux
28-33	A,B,C,E,F	American Standard	Tubular, W/T.P.'s
24-33	A,B,C,E,F	Du Pont	Hollow Fiber
24-33	A,B,C,E,F	Gulf	Spiral Wound
31-33	A,B,C,E,F	Universal	Tubular High Flux
35-36	B,C,E,F	Aerojet	Tubular High Flux
34-41	B,C,E,F	American Standard	Tubular, W/T.P.'s
34-38	B,C,E,F	Du Pont	Hollow Fiber, B-5's
38-41	B,C,E,F	Du Pont	Hollow Fiber, B-9's
33-41	B,C,E,F	Gulf	Spiral Wound
33-41	B,C,E,F	Universal	Tubular, Normal Flux
41-47	A,B,C,E,F	American Standard	Tubular, W/T.P.'s
41-49	A,B,C,E,F	Du Pont	Hollow Fiber, B-9's
41-46	A,B,C,E,F	Gulf	Gulf Spiral Wound
41-48	A,B,C,E,F	Universal	Tubular, Normal Flux
49-53	A,B,E,F	Du Pont	Hollow Fiber, B-9's
46-57	A,B,E,F	Gulf	Spiral Wound
48-57	A,B,E,F	Universal	
61-64	B,E,F	American Standard	Tubular, W/T.P.'s
57-64	B,E,F	Du Pont	Hollow Fiber, B-9's
57-66	B,E,F	Gulf	Spiral Wound
62-64	B,E	Raypak	Modified Tubular
57-64	B,E,F	Universal	Tubular, High Rejection
64-69	E,F	American Standard	Tubular, W/T.P.'s
64-66	E,F	Du Pont	Hollow Fiber B-9's
66-69	E,F	Gulf	Spiral Wound
64-68	E	Raypak	Modified Tubular
64-69	E,F	Universal	Tubular, High Rejection

SECTION IV

DATA COLLECTION

Process Variables

The operational plan for the study required that the performance of six reverse osmosis units be examined, when feasible, under six types of feed flows:

1. Full Post Treatment: reactor-clarified, sand filtered, granular activated carbon filtered, diatomaceous earth filtered, chlorinated, pH adjusted effluent.
2. Reactor-clarified, sand and granular activated carbon filtered, chlorinated, pH adjusted secondary effluent.
3. Sand and granular activated carbon filtered, chlorinated, pH adjusted effluent.
4. Reactor-clarified, sand filtered, chlorinated, pH adjusted effluent.
5. Sand filtered, chlorinated, pH adjusted effluent.
6. Chlorinated, pH adjusted effluent.

The first five post-treatment sequences were evaluated with respect to their solute removal characteristics. The permeation performances of the six reverse osmosis units were observed under conditions of "new" and "in-service" membranes, various types of flow patterns, membrane cleansing methods, etc.

Accuracy of Physical Data

Equation (18), defined in Appendix A-1, was used as the osmotic pressure correction for the reverse osmosis flux calculations. This correction is based on a number containing only one significant figure, but since the flux equation was used primarily to compare similar sets of data, percentage deviations of osmotic pressure arising from small computational inaccuracies, resulted in negligible error in the computed terminal ratios. The exclusion of an osmotic pressure factor would have caused substantial distortion in the terminal ratios.

All thermometers, water meters and pressure gauges were calibrated within their normal range of use at the start of the project. Observed data were adjusted for the small corrections at the time of measurement. These instruments were checked at irregular intervals during the study. At the study's conclusion, the instruments again were calibrated; corrections were minimal.

Random and indeterminate errors in instrument observations were estimated using the following assumed deviations:

Pressure readings	± 5 psi.
Temperatures	± 1° F.
Conductivities	It was assumed that the instrument was accurate to ± 2% and that it could be read to ± 5 micromhos.
Liquid Flow Rates	These were determined by reading the difference in the integrator reading during a stop watch measured interval of one minute. The integrator difference was recorded to ± 0.05 gal. and it was assumed that the stop watch was accurate to ± 1%.
Membrane Area	None. The areas were furnished by the manufacturer and were assumed to be correct.

Using the above assumptions within normal data ranges, the approximate experimental errors for important performance ratios were calculated:

Recovery Ratio	± 5%
Total Rejection Ratio	± 2%
Average Rejection Ratio	± 1%
Flux	± 3.5%
A Value	± 5%

None of these ratios, regarded as individual values, may be accurate beyond two significant figures. Weekly averages, which should contain compensating daily observational errors, were assumed to be accurate to three significant figures.

Errors due to individual bias were indeterminable. It was assumed that they are uni-directional with respect to each type of physical measurement and that they are largely self-compensatory in time sequence series and between inter-unit comparisons.

Sampling Methods and Frequency

During the first few months of operation, daily composite samples were taken of the feed flow to each operating reverse osmosis unit while grab samples were taken of the product and occasionally the brine flow from each unit, at times selected to coincide with the time of recording the physical data measurements. Starting in mid-July, 1970, the practice of taking daily composites of all product water samples was employed whenever feasible. In some instances this required the installation of small booster pumps on discharge lines. Brine samples were usually taken weekly and were prepared by combining two grab samples at the end of a 24 hour feed-product water compositing period. The resultant data were used primarily as material balance indicators.

Feed and discharge streams were composited for testing by continuously passing a portion of the total flow through small diameter black plastic tubing to a central bank of three-port, time-sequenced solenoid valves. At pre-determined intervals, each valve was activated by a Paragon (Model 1015-ors) timer clock to discharge a limited quantity into an individual sample bottle, housed in a household refrigerator. These samples were collected daily for analysis.

Analytical Methods

Table 2 lists the various chemical analysis methods used in this project. The results for the phosphorus and nitrogen constituents using the methods listed in the table sometimes show wide variability.

In the case of phosphorus, using the ascorbic acid method, the concentration as determined by the analyst was influenced by three factors:

1. The proper control of the reactor-clarifier (for a time the coagulator had poor internal circulation due to paint films stripping from sub-surface walls);
2. The care used in selecting and positioning matched sets of tubes as required for operation in the 880 milli-micron wavelength field of the spectrophotometer (in this case a Bausch and Lomb Spectronic 20).
3. The day-to-day performance and trends of the reverse osmosis units. (e.g. - the phosphate concentration in the product water tended to rise as phosphates were deposited on the membrane surface and would diminish again after the scale had been removed by an EDTA flush).

As the study progressed, it was found that over 95% of the total phosphorous was in the ortho form. For this reason, analysis for total phosphorous was dispensed with.

The concentration of nitrate nitrogen sometimes showed even more variability than the ortho-phosphate. This was probably caused by periodic changes in the nitrate level of the secondary effluent. It was frequently noted that a grab sample collected at the end of a twenty-four hour compositing period showed a twenty-fold difference from

Table 2. CONSTITUENT ANALYSIS METHODS

Constituent	Method	FWPCA Manual (11/69)-p.No.	Standard Methods 12th Edition p. No.	Sample Filtered Through Millipore 0.45 Micron Filter (+)=Filt'd, (-)=Unfilt'd
Acidity - $CaCO_3$(mg/l)	Methyl Orange - pH 4.5	11	47	-
Total Alkalinity-$CaCO_3$ (mg/l)	Phenylthalein & Methyl Orange	12	48	-
Ammonia Nitrogen (mg/l)	Distillation and Direct Nesslerization	-	193 (B)	-
Biochemical Oxygen Demand (mg/l)	5-day @ 20° C.	-	415	-
Boron (mg/l)	Carmine Reagent	-	63 (B)	+
Calcium (mg/l)	EDTA Titration	-	74	+
Chemical Oxygen Demand-Total and soluble (mg/l)	Dichromate - Low Level	19	-	Total - Sol. + w/inorganic binder
Chloride (mg/l)	Mercuric Nitrate Titration	-	87 (B)	+
Chlorine-Residual (mg/l)	Iodometric	-	91	-
Coliform (MPN/100 ml)	Multiple Tube Fermentation	-	567	-
Total Dissolved Solids (mg/l)	Evaporation @180° C.	257	-	+
Fluoride (mg/l)	SPADNS (w/Distillation)	-	144 & 135 C	+
Hardness - $CaCO_3$ (mg/l)	EDTA Titration	-	147 (B)	+
Nitrate-Nitrogen (mg/l)	Brucine Sulfate	165	-	+
Nitrite-Nitrogen (mg/l)	Transcribed from Treatment Plant Lab Records			-
Organic-Nitrogen (mg/l)	Distillation and Direct Nesslerization	-	403 + 392	-
Phosphorous-P, Total and Ortho	Ascorbic Acid	225	-	+
Potassium (mg/l)	Beckman Flame	-	238	+
Specific Conductance @ 25° C. (micromhos/cm)	Wheatstone Bridge (Beckman Model)			-
Sodium (mg/l)	Beckman Flame	-	238	+
Sulfate (mg/l)	Gravimetric	-	287	+
Surfactants (mg/l)	Methylene Blue	-	296	+
Suspended Solids (mg/l)	0.45 miron membrane filter @ 105° C.	-	540 (B)	+
Turbidity (J.T.U.)	Hach Model 2100	275	-	-

related composites. In some instances it appeared that the nitrate reduction occurring in the carbon towers showed an absolute concentration rather than a percentage type decrease. Since the flow in the post-treatment plant was influenced to some degree by the requirements of the reverse osmosis units, this could also result in varying nitrate levels in the R.O. feed solution. At times the concentration varied by a hundred-fold within the same week.

The nitrate analyses themselves possessed reasonably good accuracy. For example, a set of twelve spiked samples with the additions ranging from 0.0 to 10.0 mg/l nitrate nitrogen, showed average discrepancies of less than plus three per cent of the nominal values.

On the whole, all analyses appeared to be reasonably accurate. An ionic equivalent balance made in August, 1970 showed 11.2 milli-moles of cations and 10.7 milli-moles anions, or a balance within five per cent.

Further comments on the phosphate and nitrate analytical methods will be found in Appendix A-5.

Data Compatibility

The performance ratios used in evaluating the operation of the reverse osmosis units are defined and when necessary, derived in Appendix A-1. After each performance ratio was calculated for a particular time group or set of process variables, it seemed desirable to examine their mutual compatibility. This was done by making use of various material balance and rejection ratio identities.

Where observed data are internally consistent, most of these relationships yield agreement ratios equal to unity and the degree of variation from that value provides an index of error.

It should not be expected that data obtained from a demonstration study such as this, using plant scale equipment affected by numerous known, unknown, and partially controllable variables, would show the same degree of reliability or reproducibility as might be expected from smaller laboratory-type experimentation with only a few variables. It will be shown in later sections that most of the observed and computed data obtained in this study are probably accurate to plus or minus five to ten per cent. Where wide deviations occur, they may be explained as due to insufficient data, the inclusion of several incongruous data sub-sets into larger groups, probable errors in some analyses (particularly nitrates, phosphates, C.O.D., etc. which sometimes have low reproducibility ratios) or process disturbances (power outages, equipment or membrane failures, rapid membrane fouling conditions, ineffective membrane flushing operations, etc.)

The apparent accuracy of some of the tabulated data and ratios included in this report might have been improved if some data, inconsistent with the rest, had been arbitrarily deleted. This practice was avoided. Only about three data points out of many thousand were discarded and this in one single instance where their inclusion would have grossly distorted the result. It seemed preferable, instead, to present all of the available information so that the degree of accuracy of the study might be better evaluated.

SECTION V

COMPUTATIONAL METHODS

Introduction

The primary data collected during this work include transient and recorded instrument readings, results of laboratory analyses, and reports of visually observed process conditions. These data classes have been described in Section IV, which also includes a largely subjective estimate of their probable precision. It is the purpose of this section to define how these types of information were used to derive various performance ratios and to develop indices which may be employed to obtain an objective estimate of the data accuracy.

For clarification it is wise to explain the basis of the data processing methods used in this report. Since all of the work was concerned with plant-scale operations with either unknown, uncontrolled or perhaps even uncontrollable variables, and since it was felt that all data have significance of either a negative or positive nature, all data with few exceptions was included as observed or corrected.

As data accumulated, various material balance and statistical ratios (which will be described below), were developed to indicate the internal integrity of the grouped factors so that rational decisions on the probable data accuracy might be made.

Mathematical Analyses

The performance of the equipment within the post-treatment area was evaluated by determining, for each step, a "reduction ratio" applicable to a particular chemical constituent or physical property. This ratio is defined as the fraction of the particular feed constituent which was removed by the passage of the fluid through the post-treatment step, and is calculated by using Equation (15) which is defined and listed with all other numbered equations and variables in Appendix A-1.

The reason why uniquely paired data sets must be used in this equation and not the "period-averaged" analyses is discussed in detail in Section VII under the sub-heading "Data Consolidation."

For the sake of making cost breakdowns, some effort has been made to determine secondary post-treatment operating efficiencies, but extensive refinement of data was considered to be unwarranted because of the variability in the data.

When considering the permeability of the reverse osmosis units, the important performance factors are the temperature-corrected water recovery ratios (R_c), the temperature and pressure corrected A values, the tangent of the log A x 10^5 vs log time (in hours) line (b), the total rejection ratio (J_t) and the average rejection ratio (J_a).

While the symbolic notation used in this report and the algebraic equations employed in calculating the various performance factors from the raw plant data are found in the Appendices, a number of these items require further explanation.

The observed feed flow rate to a reverse osmosis unit (F_f) and the observed product flow rate (F_p) were both measured values. The reject flow rate (F_r) was determined by difference. After correcting F_p for temperature by Equation (12) to obtain F_{pc}, the corrected recovery (R_c) at 25° C conditions was determined.

From F_{pc}, using Equations (12), (17) and (1) the most important evaluation parametric value, the water permeation rate (A), was obtained. The latter value is proportional to the net effective pressure, the available membrane area, and the flow rate, (A=gr. H_2O/sq. cm-atm-sec). The value "A" was not arbitrarily chosen, but reflects a factorial kinship to the Pure Water Permeability Constant (PWP) or "A" defined by Souririjan in Reverse Osmosis (1970), page 179. The difference between the (A) and (PWP) is associated with the applied water character.

Operating specifically with pure water, the constant (PWP) varies only with pressure. The causative physical change in the membrane is known as "compaction."

When a solution is made up of multiple solutes (organic and inorganic; suspended and dissolved) the "A" value is never constant, but varies with several conditions including pressure. A saline solution depresses the "A" value and this is probably caused by "concentration polarization." The adhesive character of the solute and turbulence at the membrane surface will determine whether a time dependent decrease of "A" will also occur. The physical change causing the latter "A" depression is known as "membrane fouling." The complexity of treated and untreated secondary effluent as used in this study would cause "A" to vary/decline for all three reasons: compaction, concentration polarization, and membrane fouling.

The "A" values computed in this report are usually lower and not easily translatable into manufacturers' specified membrane values, since the units of expression may not be the same or more importantly since the manufacturers values were obtained under ideal applied-fluid conditions.

A few comments are required to indicate the precise definition and meaning of the "A value vs time" slopes (b) plotted in this report. Though some of the computed "A's" are based on "new" membrane data and others on "used" membrane data following procedural changes, initial time (t) of any data set was assumed to be the arbitrary hour one, to obtain rational slopes of (b). Zero time could not be used because the log of zero is negative infinity and is meaningless to graph.

While the above anomaly might have been avoided by redefining "A" as a semi-log relationship it was determined that this would not give a straight line plot from the test data. The data does indicate that the effect of migration of the normally present constituents into the membrane wall is a logarithmic function of time and thus requires a log-log presentation.

The amount of funds available and manufacturers' difficulties in supplying new membranes made it impossible and impractical to change membranes in accord with each feed type. An attempt was made, therefore, to minimize the fouling effects on the "A" value by using the best quality feed first and the lowest quality last.

In Sections IX through XIV, data and calculations for various consolidated time groups are presented to depict the effects of special conditions. With the effects of fouling minimized, each group should not be regarded as a fraction of the composite group data, but should be considered as individual with its own time continum.

Another area studied in this reverse osmosis project was the solute rejection characteristics of each unit. Tables will appear later depicting concentrations of the feed, product and brine flows for each unit during various time study group periods. Both average rejection ratios (J_a) and total rejection ratios (J_t) were computed, when data were available, for each of these time periods using Equations (14) and (16). These results are tabulated in the reverse osmosis unit discussion sections.

In conformity with what appears to be the usual practice, the average rejection (J_a) was calculated for each individual data set and then all of the individual J_a's were averaged to obtain the mean J_a value listed in the tabulated data. Similarly the total rejection ratios given in the tables were determined by taking the mean feed, product and brine values for the period and then calculating the total rejection (J_t) for the total period. (When J_a and J_t are based on conductivity data, Equation (12) or its equivalent must be used.)

The reason why all available solute concentration data were included in the summaries (as was also true for all permeation type information) was that one of the objectives of this project was to indicate the quality of the data obtainable from a carefully controlled demonstration project of this nature. The elimination of some data, by either statistical methods or through subjective opinions, would have destroyed the integrity of the results. It became necessary, however, as a result of this decision, to develop various internal mathematical indices which would give an idea of the probable consistency and accuracy of the included information. This was accomplished through the use of several "accuracy indicators". (See Appendix for list and derivation of all equations).

Within the reverse osmosis area several expedients were possible. Standard deviations (s_b) - Equation (22) and (s_z) - Equation (23) were determined for the various b values and water recovery ratios, while the computation of a data correlation coefficient (r) - Equation (21) provided an overall evaluation of the A vs time relationship.

The analytical data for the feed, product and brine concentrations were audited by computing a material balance agreement ratio, (E), using Equation (7), as well as the determination of various s_z values when required.

While agreement ratios E_2 and E_3 (the two are identical and are defined by Equations (8) and (9) would normally provide a means of cross-checking the internal accuracy of the R_o and J_t ratios, they were not wholly satisfactory on this project because of the slight difference in computational methods for J_a and J_t, as explained above. They did, however, provide reasonably close correlations in most instances.

Electronic Data Processing

The raw data assembled during this work include over 10,000 chemical analyses and over 45,000 individual physical observations. The numerous tables included in this report show only the selected period averages and the various derived ratios prepared from this mass of data. These calculations were made using six main programs and numerous sub-routines prepared specifically for processing this data on an IBM 1130 Computer. Since these programs were prepared to conform to this project's specific data input and printout format they may not be suitable or adaptable for use in other situations.

For the sake of brevity only one example of a daily printer output appears in Section VIII; however, a copy of the complete stack of "monthly statistic summary" printer outputs is included in Appendix A-6.

SECTION VI

SECONDARY EFFLUENT

The source water used in this study was the secondary effluent from the Hemet-San Jacinto Valley Water Reclamation Facility owned and operated by Eastern Municipal Water District (see Figure 1). Originally the plant was designed for 2.5 million gallons average daily flow. The design capacity was rapidly being reached just as the reverse osmosis project was drawing to a close. Although average daily flows were below design capacity, it was the effects of daily peak flows which indicated a need for expansion. The most apparent effects in the secondary effluent were (1) lack of nitrification and (2) high suspended solids content.

Located five miles northwest of the City of Hemet (see Figure 2) the plant operates on the conventional activated sludge principle for the treatment of primary clarified sewage. After biological treatment and final clarification, there is an optional step of disinfection by chlorination. The chlorine residual, which averaged 2.4 mg/l (range 0-7 mg/l) between March and November 1970 (weeks 1-34), took on particular significance since the program called for the discontinuance of activated carbon adsorption at the beginning of 1971.

Because activated carbon removes low concentrations of residual chlorine almost indefinitely, the aforementioned concentrations were never considered to be hazardous to the reverse osmosis membranes. With filters absent, however, the membranes could be damaged severely. In anticipation of removing the activated carbon filters, (not actually to occur until February 1971) treatment plant chlorination was terminated in November 1970. After this procedural change no detectable short or long term effects upon the membranes could be traced to the absence of chlorination. What membrane damage did occur, is attributed to membrane fouling and natural deterioration (hydrolysis) of the membrane with time. The data, for the above reasons, was not separated into sets according to "Chlorination" and "Non-Chlorination".

In addition to the treatment plant chlorination (disinfection), there was the previously mentioned pre-R.O. unit chlorination which was practiced throughout the operating period except during the first three weeks. With a range limit of 0 to 1 mg/l, the attempt was made to maintain most unit feeds at a 0.5 mg/l chlorine residual.

Table 3 is a tabulation of constituent seasonal variation of the secondary effluent. At one time it was thought that an analysis of hourly variation would be helpful, but this seemed unnecessary as all post-treated or untreated effluent water was passed through the 6,000 gallon clearwell before entering the R.O. Units. Variations of constituent concentrations were thus "buffered" in the mixing chamber, which held about one tenth of the total daily flow through the reverse osmosis plant.

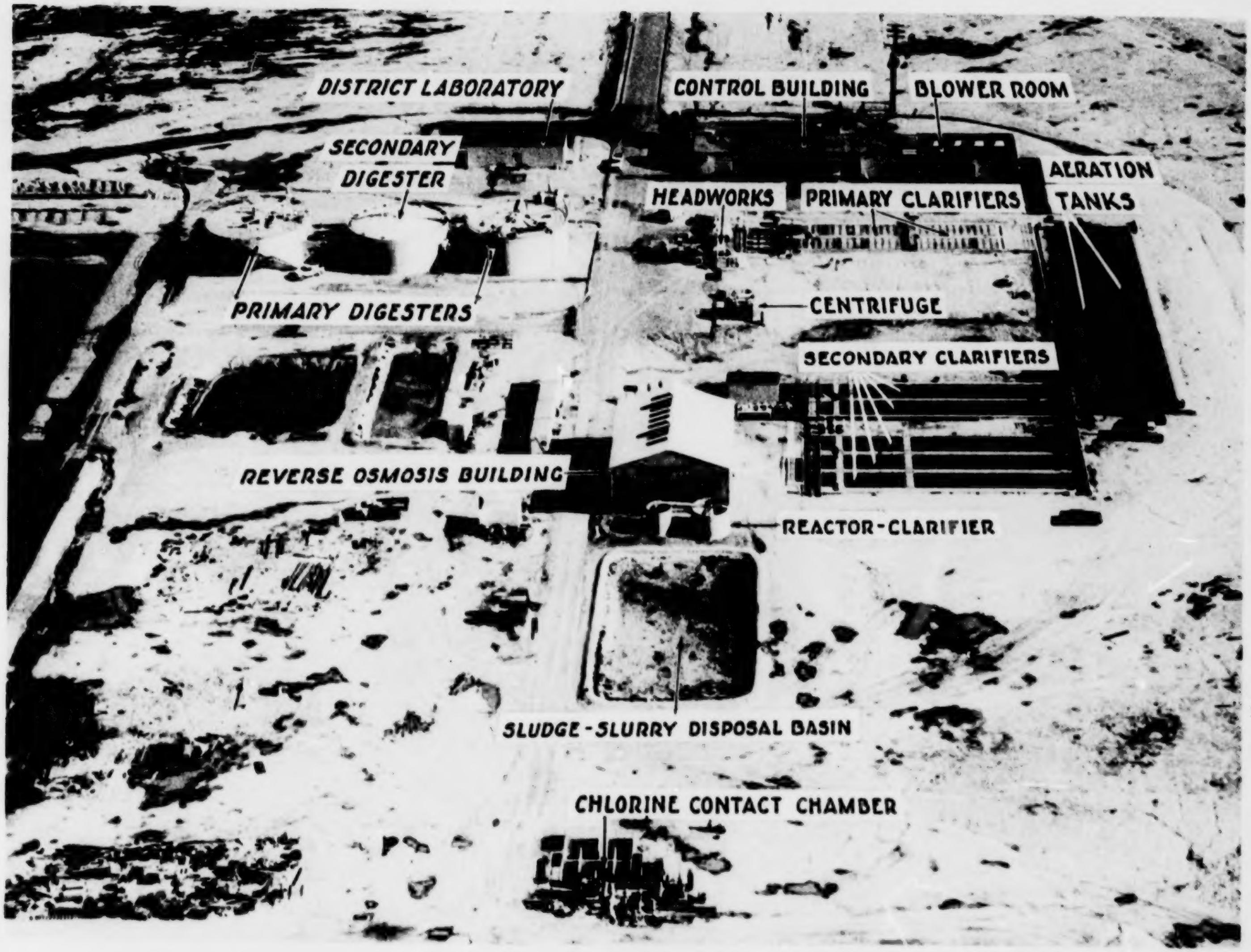

DISTRICT LABORATORY
CONTROL BUILDING
BLOWER ROOM
SECONDARY DIGESTER
AERATION TANKS
HEADWORKS
PRIMARY CLARIFIERS
PRIMARY DIGESTERS
CENTRIFUGE
SECONDARY CLARIFIERS
REVERSE OSMOSIS BUILDING
REACTOR-CLARIFIER
SLUDGE-SLURRY DISPOSAL BASIN
CHLORINE CONTACT CHAMBER

Figure 1. Aerial view of facilities

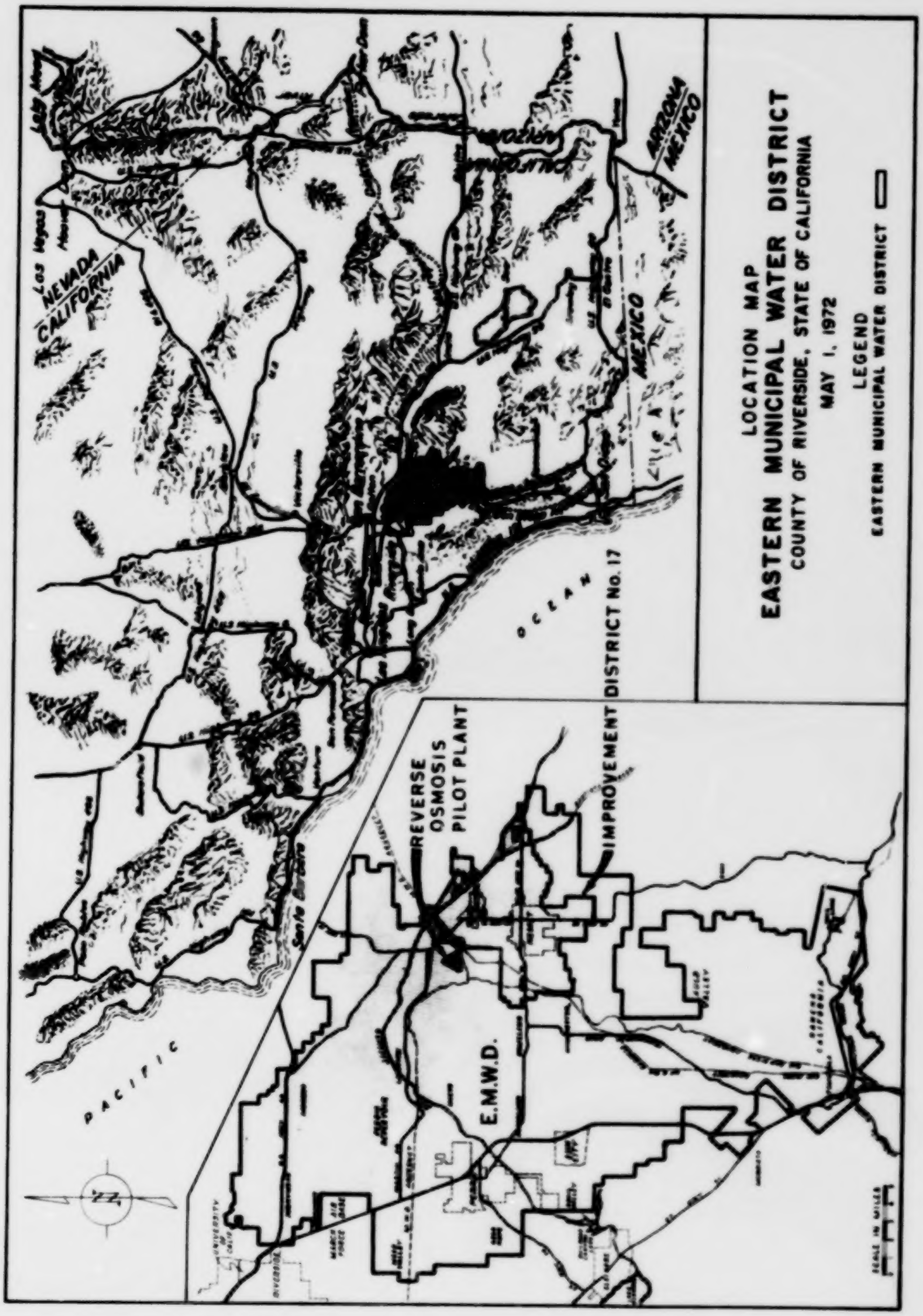

LOCATION MAP
EASTERN MUNICIPAL WATER DISTRICT
COUNTY OF RIVERSIDE, STATE OF CALIFORNIA
MAY 1, 1972
LEGEND
EASTERN MUNICIPAL WATER DISTRICT
NEVADA
CALIFORNIA
Las Vegas
ARIZONA
MEXICO
MEXICO
PACIFIC
OCEAN
Santa Barbara
REVERSE OSMOSIS PILOT PLANT
IMPROVEMENT DISTRICT No. 17
E.M.W.D.
SCALE IN MILES

Figure 2. E.M.W.D. location map

Table 3. ANALYTICAL RESULTS OF SEASONAL VARIATION IN SECONDARY EFFLUENT

(mg/1 except turbidity as J.T.U.)

Constituent	Summer 1970 July Through September	Fall 1970 October Through December	Winter 1971 January Through March	Spring 1971 April Through March	Yearly Average
Total Acidity ($CaCO_3$)	21.0	21.7	31.9	29.0	25.9
Total Alkalinity ($CaCO_3$)	230.7	224.8	225.2	250.2	232.7
B.O.D. - 5 day @ 20°	34.7	-	22.5	22.0	26.4
Calcium	54.4	72.3	65.9	63.8	64.1
Chloride	133.0	138.6	146.5	150.0	142.0
Dissolved C.O.D.	41.1	27.8	35.9	29.8	33.6
Total C.O.D.	56.5	42.3	66.4	60.5	56.4
NH_3-N	17.2	-	17.0	13.6	15.9
NO_3-N	5.4	6.6	10.0	4.9	6.7
Organic N	3.0	-	4.0	3.4	3.5
Ortho-P	14.2	15.1	13.8	12.5	13.9
Dissolved Oxygen	2.8	-	-	0.4	1.6
Sulfate	154.0	164.0	175.0	152.0	161.0
Suspended Solids	6.4	11.1	16.0	8.0	10.4
T. D. S.	725.0	694.0	723.0	720.0	716.0
Total Hardness ($CaCO_3$)	208.0	232.0	241.0	231.0	228.0
Turbidity	4.6	7.7	14.0	6.7	8.2

Table 4 depicts the average quality of domestic water supply to the sewered areas of the Eastern Municipal Water District. The constituent levels are weighted for the volumetric contributions from the three main water sources in the Valley: Colorado River, wells and Lake Hemet. It can be seen that the sodium and chloride constituent levels are much higher in the secondary effluent than in the domestic waters and this accounts for the percentage difference between TDS levels. Waters enter the domestic supply system below the recommended levels of TDS, and increases approximately 30% by the time it reaches the treatment facility. Through research, it is now believed that the incremental increase of sodium chloride is due to the domestic and commercial water softeners operating in the Valley to counter the effects of hardness.

To have this highly saline water enter the closed basin underground reservoir in increasing quantities would cause a deterioration of the latter. Removing the salt before percolation would protect the groundwater reservoir at least from domestic waste water refractories.

Table 4. DOMESTIC WATER QUALITY TO SEWERED AREAS OF E.M.W.D.

COMPARED TO SECONDARY EFFLUENT
(mg/l)

Constituent	Domestic Water	Secondary Effluent
Boron	0.3	0.4
Chloride	62	142
Fluoride	0.5	0.6
Hardness	245	241
Sodium	57	147
Sulfate	122	161
T.D.S.	493	716

SECTION VII

POST-TREATMENT OF SECONDARY EFFLUENT

Introduction

Discussion of post treatment can be divided into two categories: "physical performance characteristics" and "operating costs." The first will be discussed presently. The second is more appropriately reviewed in Section XVI, "Reverse Osmosis Costs".

Scope of Post-Treatment Operations

Facilities (Figure 3) were provided for the five major secondary effluent treatments. Four of these are discussed in detail below:

1. Reactor-clarification with cationic polymer and alum injection. Purpose: to aid in the removal of residual suspended solids. This was accomplished in the 15.5 ft. diameter, open-top coagulator with a side wall height of 10.5 ft. and a capacity of 15,000 gallons (Figure 4). With this capacity, the retention time was 2.4 hours and the overflow rate was 0.55 gpm/sq. ft. Operating on the sludge blanket principle, the tank was provided with a rim mounted overflow launder, a slow-moving electrically-propelled mixer blade and chambers for chemical mixing and sludge separation. An influent controller, which was activated on water consumption demand, had a discharge rating of 125 GPM, the maximum possible flow rate through the clarifier. A single 10 HP electric motor Aurora pump fed the clarifier. Equipment was also provided for automatic sludge or slurry removal. Clarification was accomplished in the clarifier with the aid of two chemicals: alum and Calgon cationic polyelectrolyte #ST-260. Best operation seemed to occur using these chemicals in the following proportions: polymer, 0.5 to 0.75 mg/l; alum 70 to 100 mg/l. Both chemicals were added at the same point in the mixing chamber. Routine jar tests helped the operator to determine the appropriate dosages.

2. Sand Filtration (See Figure 5). Purpose: to remove suspended solids. The set of three filters were designed for a total flow rate of about 2 to 3 gal./sq. ft-min., but were normally operated at about one-third that rate (1 gal/sq. ft-min. or 16 gal. min. downflow rate). The three 54 in. diameter 60 in. shell height pressure sand filters were normally operated in parallel. Each was packed from the bottom up with the following layers:

   8 in. with 1 1/2 to 1 in. gravel
   2 1/2 in. with 1 in. to 1/2 in. gravel
   2 1/2 in. with 1/2 in to 1/4 in. gravel

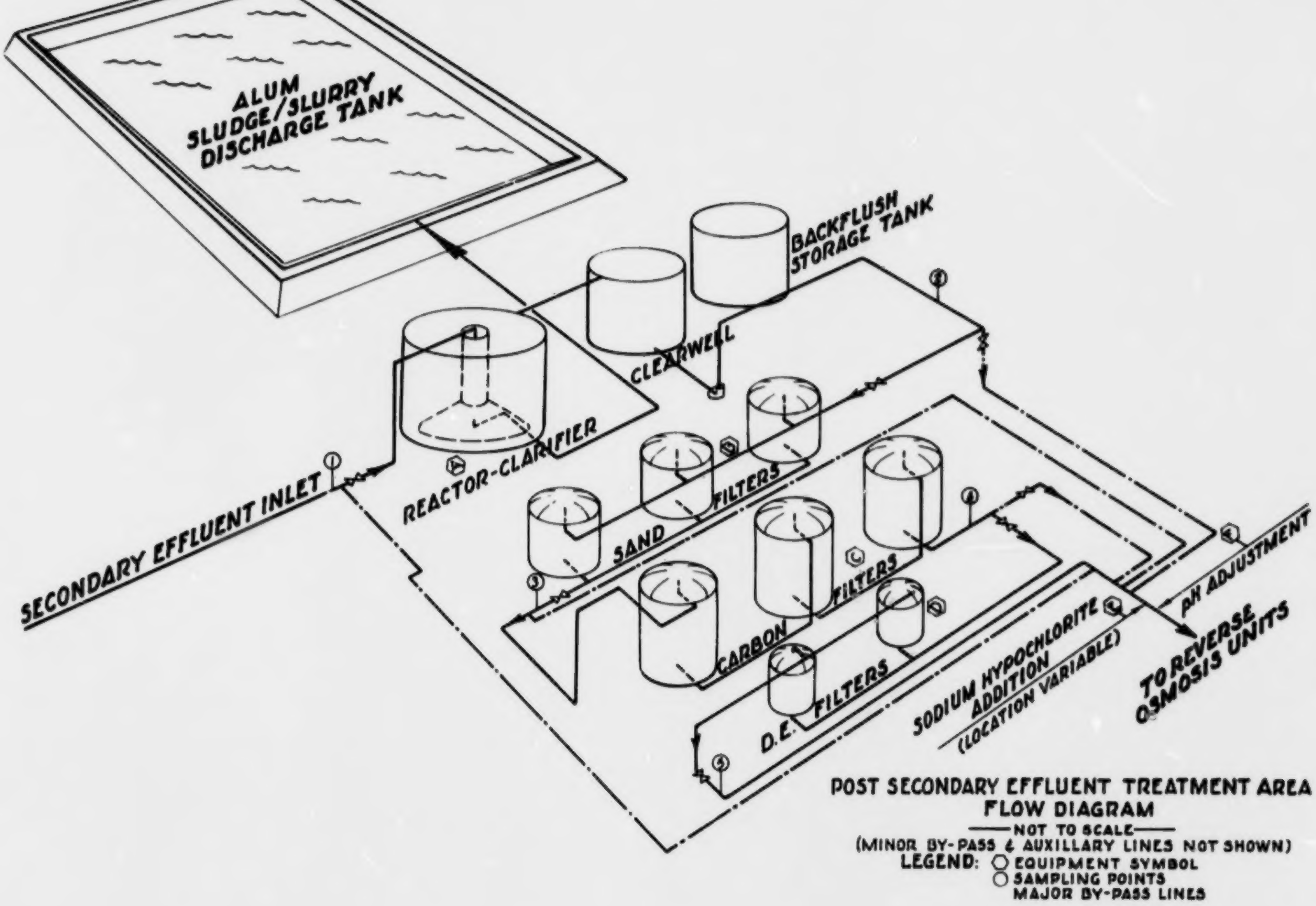

ALUM SLUDGE/SLURRY DISCHARGE TANK
BACKFLUSH STORAGE TANK
CLEARWELL
REACTOR-CLARIFIER
SECONDARY EFFLUENT INLET
SAND FILTERS
CARBON FILTERS
D.E. FILTERS
SODIUM HYPOCHLORITE ADDITION
(LOCATION VARIABLE)
pH ADJUSTMENT
TO REVERSE OSMOSIS UNITS
POST SECONDARY EFFLUENT TREATMENT AREA
FLOW DIAGRAM
NOT TO SCALE
(MINOR BY-PASS & AUXILLARY LINES NOT SHOWN)
LEGEND: EQUIPMENT SYMBOL
SAMPLING POINTS
MAJOR BY-PASS LINES

Figure 3. Post secondary effluent treatment facilities

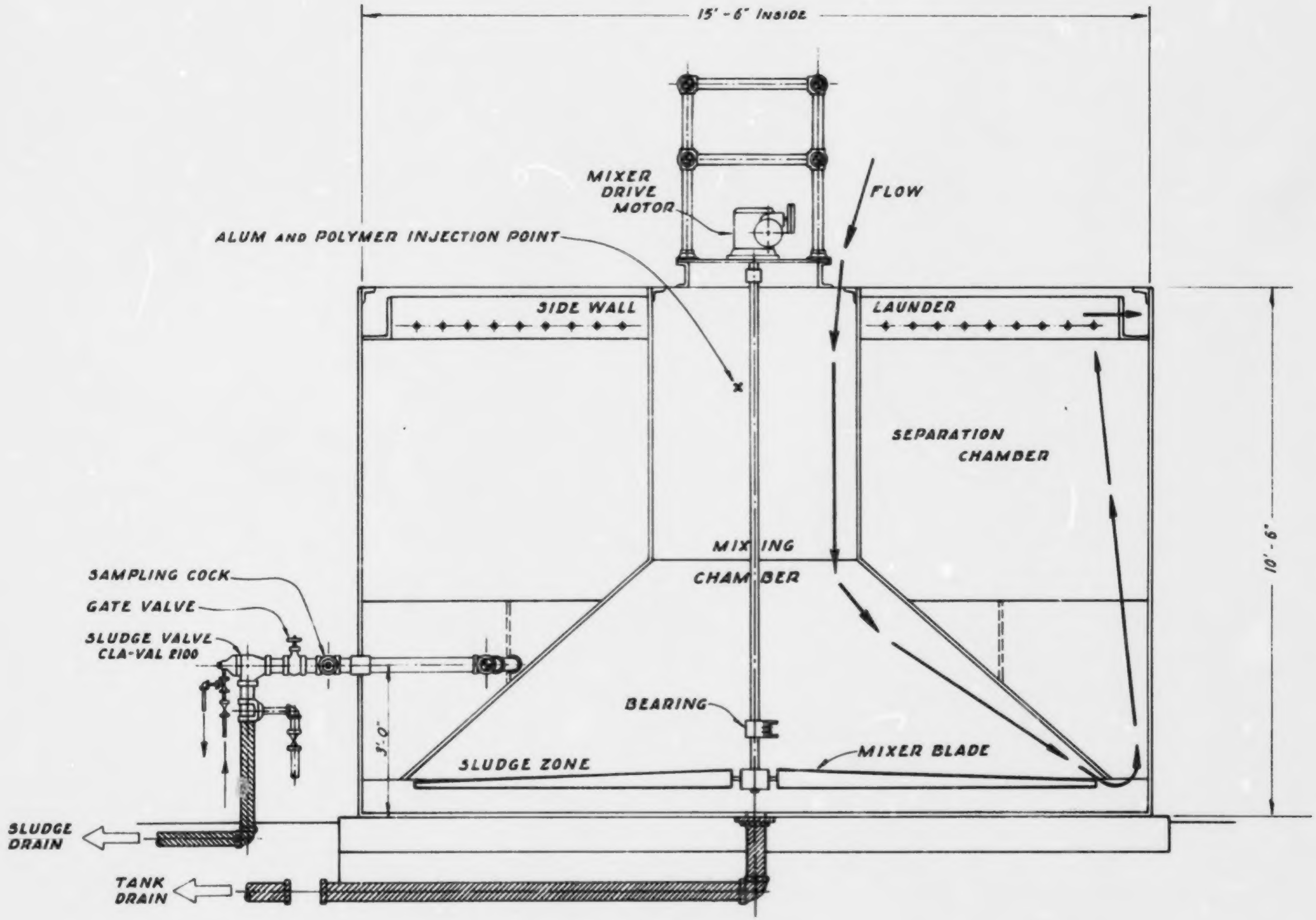

15' - 6" INSIDE
MIXER DRIVE MOTOR
FLOW
ALUM AND POLYMER INJECTION POINT
SIDE WALL
LAUNDER
SEPARATION CHAMBER
10' - 6"
MIXING CHAMBER
SAMPLING COCK
GATE VALVE
SLUDGE VALVE CLA-VAL 2100
BEARING
MIXER BLADE
3'-0"
SLUDGE ZONE
SLUDGE DRAIN
TANK DRAIN

Figure 4. Reactor-clarifier

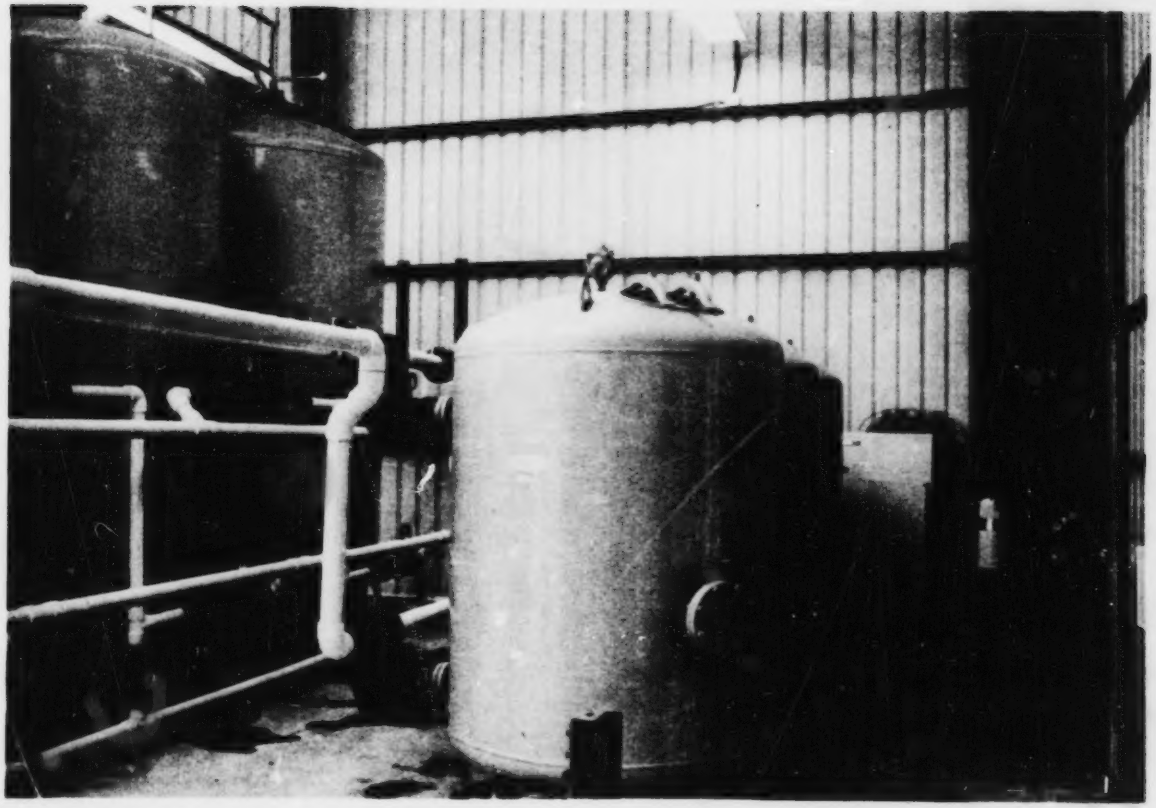


Figure 5. Sand filters (right) and activated carbon filters (left)

3 in. with 1/4 in. to 1/8 in. gravel
3 in. with #12 sand (.8 to 1.2 mm)
21 in. of #16 filter sand (145 to .55 mm)

Each filter vessel was fed at the top through a centrally located 3 in. pipe and was drained from the bottom through 8 symmetrically located cross-chord 3/4 in. laterals, with a tank total of 60 - 1/4 in. holes on 6 in. centers.

The sand filters were backwashed, either when the discharge pressure fell about 20 psi below the normal feed pressure of 100 psi or when the discharge turbidity or suspended solids content increased abruptly. While in use, the sand filters were backwashed with four types of wash water: reactor clarifier effluent, activated carbon filter effluent and diatomaceous filter effluent. The rate of backwashing varied considerably but averaged 9 GPM/sq. ft.

3. Granular Activated Carbon Filtration. Purpose: to remove residual organics. For this filtration, three 72 in. diameter by 120 in. shell height pressure carbon towers were employed. They were operated in series at a hydraulic loading rate of one-third the design rate of [illegible] gal/sq. ft-min. Each tower was packed the same as the sand filter through the #12 sand layer, but on top, in place of the #16 sand, there was a 68 in. layer of activated carbon, purchased under the trade name of "Filtrasorb 400®" of the Calgon Corporation. The activated carbon had the following physical properties and met the specifications listed below:

Table 5. ACTIVATED CARBON PHYSICAL PROPERTIES AND SPECIFICATIONS

Total surface area (N_2 BET method) M^2/g	950-1050
Bed density backwashed and drained, lbs/ft^3	26
Particle density wetted in water g/cc	1.3-1.4
Pore volume cc/g	0.85
Effective size mm	0.8-0.9
Uniformity coefficient	1.9 or less
Sieve Size U.S. Std. Series	
Larger than No. 8 - Max %	8
Smaller than No. 30 - Max %	5
Mean Particle Diam. mm	1.5-1.7
Iodine Number, Min	900
Abrasion Numer, Min.	70 (ASTM D 2355)
Ash Max %	8
Moisture as packed, Max %	2.0

The carbon filters were backwashed with various post-treatment process effluents when vessel pressure drops exceeded 10 to 20 psi. Backwash flow rates were usually on the order of 4-5 GPM per sq. ft. A record of backflushes according to post-treatment unit equipment appears in Table 6, while dates, volumes, and duration of backflushes appear in the Appendix Section A-4.

4. Diatomaceous Earth Filtration, Purpose: to provide final polishing prior to reverse osmosis units. For this two D.E. pressure filters were operated in parallel, each having a 30 inch diameter and a 48 inch shell height. Both filters contained thirty-one vertically-positioned polypropylene-covered cycolac filter elements. Such elements were 48 inches long and 3 inches in diameter. Estimated filtration area was 97 sq. ft. per vessel. Accessory equipment to the D.E. filter included two pre-coat preparation pots and a filter body feed tank. Of the post-treatment processes, the D.E. filters seemed to present the most problems. Essentially all problems were related to pre-coating of the filter element tubes: according to the person in charge of the units, "There was always a question as to whether coatings were uniform and of the appropriate thickness." In addition, prevention of pre-coat wash-outs during filter operations was not always assured, as pressure fluctuations in passing from "wasting" to "on stream" could facilitate a wash-out of filter media. Potential for wash-out was reduced substantially by manipulation of the discharge piping. Installation of observation ports would have given additional insurance in forming uniform filter coatings, but time did not permit as D.E. filters were the first equipment to be removed from the post-treatment area. The D.E. filters were operated for five months with considerable "down" time. Except for brief periods of singular operation, the D.E. filters were operated in parallel.

Equipment and Facilities

All of the equipment and facilities which were part of this project, including the laboratory, a small office and storage area, but excluding the reactor-clarifier, clear-well, flushing water storage tank and waste ponds (which were located in the nearby area) were housed in a rigid frame building with an adequately drained concrete floor. The building was approximately 62 ft. by 50 ft. with 20 ft. high walls. (See Figure 1) The temperature of the building in the operation area was uncontrolled for the most part although two forced-air heaters were available to prevent frozen pipes in winter.

It should be remembered that pH adjustment is a step in post-treatment, but because of its close association and necessity to the reverse osmosis units, it is discussed in sections specific for the R.O. units.

Table 6. POST-SECONDARY TREATMENT BACKFLUSH RECORD

Week No.	Sand.	Carbon	D.E.
2	X		
3	X		
5	X	X	
6	X	2X	
7		X	2X
8		X	
10	X		
12		X	
13	X	X	X
15	X		X
16		X	
17	X		X
19			X
20	X		X
21			X
22	X	X	
23			X
24	X		X
26	X		
27		X	
28	X		
30	X	X	2X OFF
36	X		
37		X	
39		X	
41	X		
42		X	
43	X		
44		2X OFF	
49	3X		
51	X		
52	X		
53	X		
54	2X		
55	X		
56	2X		
57	X		
58	2X		
59	2X		
60	X		
61	X		
62	3X		
63	X		
Total No. Flushes Per Time on Stream	39/63 weeks	16/44 weeks	12/30 weeks

Immediately outside the building were three reservoirs: the reactor-clarifier, clear-well and a backflush water storage tank. The latter two were identical with 10.5 ft. high side walls, 10 foot diameters and 6,000 gallon capacities. Except for the final period of no post-treatment, the clear-well always contained the product of the reactor-clarifier.

Alternatively, the backflush tank stored both post-treatment effluent and Colorado River Water at various times during the project.

A fourth reservoir made of sand with vinyl plastic sealed floor was constructed to receive reactor-clarifier sludge/slurry discharge. The reservoir's design capacity was 110,000 gallons with dimensions of 50' x 100' x 3'.

Miscellaneous Post-Treatment Equipment Specifications and General Comments

Cross connections and by-pass piping were installed to backwash the sand, carbon and D.E. filters and to modify or skip one or more of the sequential, post-treatment processes. Thus, while full treatment of secondary effluent included reactor-clarification followed by passage through 3 sand filters, 3 carbon filters and 2 D.E. filters, there were times when each (either singly or in combination), was removed from service. However, it was impossible to invert the post-treatment sequence: for example, to send carbon filtered effluent through the reactor-clarifier.

Backwashing was accomplished with a 2 X 2 1/2 X 9A -GBPA Aurora Pump powered by a 15 horse power 3,500 RPM, 3 phase, 230/460 volt motor; two inch Hendy flow meters at each step provided both total flow and instantaneous flow rates. Total flows and instantaneous rates were recorded manually. Alternatively the reverse osmosis units required an accurate record of flow and pressure patterns. To serve these purposes Barton Models 242 and 208 A (pressure and flow recorders respectively) were employed.

For coating the D.E. filter elements and reactor-clarifier alum injection, a diaphragm duplex type, BIF model 1210-05-9109 pump was installed. Its head for D.E. transport, was 0-8 GPH at 125 pounds discharge pressure. The alum injection head for the same pump was capable of 2 GPH at 125 psi discharge pressure. The power source was a 1/6 horse power, 115 volt, 60 cycle motor through an adjustable V-belt.

At various times during the project, air bumps were needed to help remove the more adhesive coatings of impurities from both the post-treatment filters and the reverse osmosis units. A Speedaire Model 12991, 1 horse power compressor provided the air to facilitate air bumping. Air bumping was an irregular practice, and no single criterion was used to justify the need for an air bump.

With only a few exceptions, the process piping used was P.V.C. 1220 and performed adequately.

Data Consolidation

The post-treatment constituent data were averaged into weekly groups to reflect the effects of the various post-treatment sequences. These data are shown in the influent-effluent columns of Tables 7 through 12. Included in these tables are the applicable "reduction ratios" based upon the change in concentration of a particular constituent before and after a specified post-treatment step or steps. These "reduction ratios", which are similar to the total rejection ratios used in the evaluation of reverse osmosis, were calculated as:

$$J_{fp} \doteq 1 - (J_p/J_f) \qquad (15)$$

where J_p and J_f are the concentrations of a given constituent in the "product" (in this case the discharge) and the "feed" flows respectively.

It is important to realize that the reduction ratio was not calculated from the list of influent and effluent data. In order to obtain more significant information, the reduction ratio was calculated only from paired influent/effluent data from each individual week and the ratios for all weekly periods were then averaged to obtain the period mean.

A copy of a speciment computer printout for weeks 16-33 (selected at random from the complete set of about 130) is shown as Table 13. The column headings, which were chosen for ease in the interpretation of the printout, require some explanation.

Code:	PT12 indicates a post-treatment area sampling point, PT meaning that a secondary effluent feed sample analysis (point 1) is being compared with the reactor-clarifier effluent analysis (point 2). The numeral 3 would indicate the sand filters, 4 the carbon filters and 5 the D.E. filters.
Run Analysis:	PS04 signifies a post treatment process analysis for sulfate.
Feed and Product:	First set, columns 3 and 4; these show the average levels for the number of paired sets available, as indicated in column 6. Second set, columns 7 and 8; show the averages of all sample analyses made in the designated time period. NF is the total number of feed samples and NP the total number of product (outflow) samples.
Rejection:	This is the calculated total rejection in per cent. (J_{fp} X 100) as defined by Equation (15).

Zero's indicate missing data, not the absence of the solute.

Table 7. POST-SECONDARY TREATMENT UNIT CONSTITUENT ANALYSES

UNIT: REACTOR-CLARIFIER; INFLUENT SOURCE: SECONDARY EFFLUENT

(mg/1 except turbidity as J.T.U.)

Constituent	Weeks 1-15			Weeks 16-33		
	Influent	Effluent	Reduction Ratio	Influent	Effluent	Reduction Ratio
Acidity	-	-	-	20.36	27.18	-.231
Alkalinity	208.67	-	-	232.59	193.00	.174
B.O.D.	32.57	-	-	39.25	-	-
Calcium	62.53	-	-	55.62	54.70	.085
Chloride	128.00	-	-	133.00	123.33	.040
Dissolved C.O.D	54.59	29.55	.382	41.52	22.66	.454
Total C.O.D.	62.41	29.17	.505	55.97	32.39	.432
NH_3-N	17.31	-	-	17.06	15.23	.046
NO_3-N	9.64	6.30	.406	6.12	4.47	.361
Organic N	-	-	-	2.50	2.23	.153
Ortho-P	14.00	-	-	18.75	10.65	.432
Sulfate	159.20	-	-	153.00	173.78	-.196
Suspended Solids	9.50	-	-	7.31	9.60	-.297
T.D.S.	781.85	690.00	.151	713.60	679.89	.039
Total Hardness	232.44	-	-	214.19	196.21	.071
Turbidity	5.65	2.36	.581	4.86	3.50	.293

Table 7 Cont'd. POST-SECONDARY TREATMENT UNIT CONSTITUENT ANALYSES

UNIT: REACTOR-CLARIFIER; INFLUENT SOURCE: SECONDARY EFFLUENT

(mg/l except turbidity as J.T.U.)

Constituent	Weeks 42-48			Weeks 49-57		
	Influent	Effluent	Reduction Ratio	Influent	Effluent	Reduction Ratio
Acidity	30.99	40.90	-.320	31.34	38.07	-.214
Alkalinity	218.86	177.57	.189	223.67	202.22	.096
B.O.D.	-	-	-	22.50	-	-
Calcium	72.00	69.00	.014	65.22	63.44	.027
Chloride	138.00	-	-	149.75	-	-
Dissolved C.O.D.	32.33	26.27	.188	38.65	28.38	.266
Total C.O.D.	57.63	40.05	.305	69.06	45.68	.338
NH_3-N	-	-	-	17.00	-	-
NO_3-N	6.85	9.53	-.39	11.55	9.72	.158
Organic N	-	-	-	4.00	-	-
Ortho-P	14.67	7.26	.505	13.27	8.47	.362
Sulfate	186.20	223.25	-.176	169.33	185.00	-.076
Suspended Solids	10.33	5.33	.484	17.00	9.60	.435
T.D.S.	738.33	785.00	-.063	707.78	575.00	.135
Total Hardness	243.43	238.14	.022	234.89	230.00	.021
Turbidity	6.85	3.90	.438	16.69	8.88	.467

Table 8. POST-SECONDARY TREATMENT UNIT CONSTITUENT ANALYSES

UNIT: SAND FILTER; INFLUENT SOURCE: SECONDARY EFFLUENT

(mg/l except turbidity as J.T.U.)

Constituent	Weeks 34-41			Weeks 58-63		
	Influent	Effluent	Reduction Ratio	Influent	Effluent	Reduction Ratio
Acidity	20.02	24.58	-.227	30.65	32.32	-.054
Alkalinity	232.12	240.00	-.034	246.83	254.83	-.032
B.O.D.	-	-	-	-	-	-
Calcium	80.00	-	-	61.83	61.33	.008
Chloride	139.50	138.50	.082	155.33	172.00	-.01
Dissolved C.O.D.	26.90	26.07	.046	25.72	23.76	.076
Total C.O.D.	42.61	39.21	.104	60.48	41.87	.308
NH_3-N	-	-	-	-	-	-
NO_3-N	6.97	5.67	.201	6.60	-	-
Organic N	-	-	-	-	-	-
Ortho-P	14.86	14.20	.028	13.20	13.18	.001
Sulfate	166.00	164.80	.011	145.0	145.0	.000
Suspended Solids	13.40	7.00	.478	-	-	-
T.D.S.	706.25	689.00	.007	721.67	714.17	.010
Total Hardness	234.00	232.88	.005	223.17	221.50	.008
Turbidity	9.15	4.80	.475	9.65	3.53	.634

Table 9. POST-SECONDARY TREATMENT UNIT CONSTITUENT ANALYSES

UNIT: SAND FILTERS; INFLUENT SOURCE: REACTOR-CLARIFIER

(mg/l except turbidity as J.T.U.)

Constituent	Weeks 1-15			Weeks 16-33		
	Influent	Effluent	Reduction Ratio	Influent	Effluent	Reduction Ratio
Acidity	-	-	-	27.18	25.92	.012
Alkalinity	-	-	-	193.00	212.70	-.022
B.O.D.	-	-	-			
Calcium	-	-	-	54.70	46.44	.049
Chloride	128.00	-	-	123.33	-	
Dissolved C.O.D.	29.55	24.95	.156	22.66	20.35	.102
Total C.O.D.	29.17	29.23	-.002	32.39	25.22	.221
NH_3-N	-	-	-	15.23	-	-
NO_3-N	6.30	-	-	4.47	2.70	.090
Organic N	-	-	-	2.23	-	-
Ortho-P	-	-	-	10.65	9.77	.083
Sulfate	-	-	-	173.78	-	-
Suspended Solids	-	-	-	9.60	3.00	.688
T.D.S.	690.00	703.57	-.008	679.89	713.00	-.080
Total Hardness	-	-	-	196.21	191.71	.014
Turbidity	2.36	1.30	.450	3.50	1.32	.624

Table 9 Cont'd. POST-SECONDARY TREATMENT UNIT CONSTITUENT ANALYSES

UNIT: SAND FILTERS; INFLUENT SOURCE: REACTOR-CLARIFIER

(mg/l except turbidity as J.T.U.)

Constituent	Weeks 42-48			Weeks 49-57		
	Influent	Effluent	Reduction Ratio	Influent	Effluent	Reduction Ratio
Acidity	40.90	39.66	.030	38.07	38.67	-.016
Alkalinity	177.57	184.71	-.040	202.22	206.44	-.021
B.O.D.	-	-	-	-	2.70	-
Calcium	69.00	69.50	-.007	63.44	62.67	.012
Chloride	-	125.00	-	-	143.57	-
Dissolved C.O.D.	26.27	17.50	.334	28.38	25.62	.097
Total C.O.D.	40.05	33.55	.162	45.68	35.42	.225
NH_3-N	-	-	-	-	-	-
NO_3-N	9.53	9.77	-.024	9.72	8.10	.167
Organic N	-	-	-	-	-	-
Ortho-P	7.26	9.00	-.239	8.47	8.18	.034
Sulfate	223.25	-	-	185.00	189.38	-
Suspended Solids	5.33	3.00	.437	9.60	3.20	.667
T.D.S.	785.00	738.00	.022	575.00	690.56	-.201
Total Hardness	238.14	232.40	.024	230.00	227.38	.010
Turbidity	3.90	2.32	.405	8.88	2.60	.713

Table 10. POST-SECONDARY TREATMENT UNIT CONSTITUENT ANALYSES

UNIT: CARBON FILTERS; INFLUENT SOURCE: SAND FILTERS

(mg/l except turbidity as J.T.U.)

Constituent	Weeks 34-41		
	Influent	Effluent	Reduction Ratio
Acidity	24.58	25.14	-.023
Alkalinity	240.0	254.0	-.058
B.O.D.	-	-	-
Calcium	-	74.00	-
Chloride	138.50	136.00	.054
Dissolved C.O.D.	26.07	5.76	.779
Total C.O.D.	39.21	10.84	.724
NH_3-N	-	-	-
NO_3-N	5.67	0.86	.845
Organic N	-	-	-
Ortho-P	14.20	14.00	.014
Sulfate	164.80	165.63	-.003
Suspended Solids	7.00	0.40	.943
T.D.S.	689.00	688.75	.025
Total Hardness	232.88	226.62	.027
Turbidity	4.80	0.46	.905

Table 11. POST-SECONDARY TREATMENT UNIT CONSTITUENT ANALYSES

UNIT: CARBON FILTERS; INFLUENT SOURCE: REACTOR CLARIFIER AND SAND FILTERS

(mg/1 except turbidity as J.T.U.)

Constituent	Weeks 1-15			Weeks 16-33		
	Influent	Effluent	Reduction Ratio	Influent	Effluent	Reduction Ratio
Acidity	-	-	-	25.92	20.05	.299
Alkalinity	-	-	-	212.70	220.80	-.068
B.O.D.	-	-	-	-	1.20	-
Calcium	-	-	-	46.44	53.16	-.037
Chloride	-	-	-	-	130.50	-
Dissolved C.O.D.	24.95	15.32	.656	20.35	5.37	.736
Total C.O.D.	29.23	15.09	.638	25.22	6.96	.724
NH_3-N	-	-	-	-	14.57	-
NO_3-N	-	-	-	2.70	3.37	-.248
Organic N	-	-	-	-	4.28	-
Ortho-P	-	-	-	9.77	8.76	.103
Sulfate	-	-	-	-	171.71	-
Suspended Solids	-	-	-	3.00	0.60	.800
T.D.S.	703.57	681.82	.034	713.00	640.42	-
Total Hardness	-	-	-	191.71	201.92	-.051
Turbidity	1.30	.53	.591	1.32	0.35	.766

Table 11 Cont'd. POST-SECONDARY TREATMENT UNIT CONSTITUENT ANALYSES

UNIT: CARBON FILTERS; INFLUENT SOURCE: REACTOR-CLARIFIER AND SAND FILTERS

(mg/l except turbidity as J.T.U.)

Constituent	Weeks 42-48			Weeks 49-57		
	Influent	Effluent	Reduction Ratio	Influent	Effluent	Reduction Ratio
Acidity	39.66	41.34	-.042	38.67	35.80	-.170
Alkalinity	184.71	195.29	-.057	206.44	210.00	-.111
B.O.D.	-	-	-	2.70	-	-
Calcium	69.50	69.50	0	62.67	65.00	-.015
Chloride	125.00	129.67	-.037	143.57	180.00	-
Dissolved C.O.D.	17.50	3.93	.775	25.62	-	-
Total C.O.D.	33.55	7.62	.773	35.42	3.80	.910
NH_3-N	-	-	-	-	-	-
NO_3-N	9.77	5.17	.471	8.10	-	-
Organic N	-	-	-	-	-	-
Ortho-P	9.00	-	-	8.18	-	-
Sulfate	-	213.20	-	189.38	180.00	-
Suspended Solids	3.00	0.00	1.000	3.20	0.00	1.000
T.D.S.	739.33	698.33	.016	690.56	650.00	.058
Total Hardness	232.40	234.75	-.001	227.38	235.00	-.043
Turbidity	2.32	0.35	.853	2.60	0.40	.967

Table 12. POST-SECONDARY TREATMENT UNIT CONSTITUENT ANALYSES

UNIT: D.E. FILTERS; INFLUENT SOURCE: REACTOR-CLARIFIER, SAND AND CARBON FILTERS

(mg/l except turbidity as J.T.U.)

Constituent	Weeks 1-15			Weeks 16-28		
	Influent Influent	Effluent Effluent	Reduction Ratio	Influent	Effluent	Reduction Ratio
Acidity	-	-	-	21.56	20.22	.058
Alkalinity	-	-	-	223.85	216.88	.004
B.O.D.	-	-	-	1.20	0.90	.250
Calcium	-	-	-	54.28	55.22	-.017
Chloride	-	-	-	132.60	134.29	-.049
Dissolved C.O.D.	15.32	9.23	.266	5.79	5.38	.025
Total C.O.D.	15.09	9.11	.010	7.36	7.10	.036
NH$_3$-N	-	-	-	14.26	14.46	-.104
NO$_3$-N	-	-	-	5.60	4.38	.017
Organic N	-	-	-	4.28	2.76	.402
Ortho-P	-	-	-	9.73	9.90	-.017
Sulfate	-	-	-	163.00	169.00	-.049
Suspended Solids	6.00	6.00	0	1.00	0.00	1.000
T.D.S.	681.82	686.88	-.007	646.43	662.54	.024
Total Hardness	-	-	-	199.50	204.00	-.002
Turbidity	0.53	0.44	.126	0.36	0.29	.227

Table 13. POST TREATMENT DATA WEEKS 16 THROUGH 33

PRETREATMENT DATA, WEEKS 16 THROUGH 33

CODE	RUN ANALYSIS	FEED	PRODUCT	REJECTION	PAIRS	FEED	PRODUCT	NF	NP
PT12	PSO4	148.00	177.00	19.58-	6	153.00	173.78	7	9
PT13	PSO4	.00	.00		0	153.00	.00	7	0
PT14	PSO4	146.80	174.60	18.93-	5	153.00	171.71	7	7
PT15	PSO4	157.00	167.50	6.68-	4	153.00	168.10	7	10
PT23	PSO4	.00	.00		0	173.78	.00	9	0
PT24	PSO4	175.14	171.71	1.96	7	173.78	171.71	9	7
PT25	PSO4	169.83	163.00	4.02	6	173.78	168.10	9	10
PT34	PSO4	.00	.00		0	.00	171.71	0	7
PT35	PSO4	.00	.00		0	.00	168.10	0	10
PT45	PSO4	169.50	168.25	.74	4	171.71	168.10	7	10
PT12	PTDS	713.60	685.53	3.93	15	713.60	679.89	15	18
PT13	PTDS	742.00	713.00	3.91	1	713.60	713.00	15	1
PT14	PTDS	686.44	650.00	5.31	9	713.60	640.42	15	12
PT15	PTDS	727.00	668.58	8.04	12	713.60	659.53	15	15
PT23	PTDS	743.00	713.00	4.04	1	679.89	713.00	18	1
PT24	PTDS	662.50	640.42	3.33	12	679.89	640.42	18	12
PT25	PTDS	680.53	659.53	3.09	15	679.89	659.53	18	15
PT34	PTDS	.00	.00		0	713.00	640.42	1	12
PT35	PTDS	713.00	720.00	.97-	1	713.00	659.53	1	15
PT45	PTDS	640.56	633.11	1.16	9	640.42	659.53	12	15
PT12	PTHARD	211.307	196.231	7.13	13	214.187	196.214	16	14
PT13	PTHARD	203.571	191.714	8.52	7	214.187	191.714	16	7
PT14	PTHARD	207.916	202.416	2.65	12	214.187	201.923	16	13
PT15	PTHARD	212.600	204.600	3.76	10	214.187	203.818	16	11
PT23	PTHARD	194.428	191.714	1.40	7	196.214	191.714	14	7
PT24	PTHARD	197.916	201.583	1.84-	12	196.214	201.923	14	13
PT25	PTHARD	192.700	201.600	4.61-	10	196.214	203.818	14	11
PT34	PTHARD	191.714	201.428	5.06-	7	191.714	201.923	7	13
PT35	PTHARD	183.060	196.750	7.50-	4	191.714	203.818	7	11
PT45	PTHARD	198.500	198.750	.12-	8	201.923	203.818	13	11

Unlike chemical levels within the reverse osmosis test area, the consistency of which may be evaluated through material balance correlations, etc. (as discussed in a number of other sections of this report), the accuracy of the post-treatment analytical data was inferred only by computing standard deviations for integral sets. Random checking of such deviations has led to the conclusion that under the existent test conditions the rejection ratio method used yields information of greater internal consistency than ratios of either the constituent discharge level from each stage to the constituent level of the secondary effluent or the mol fraction reduction of each item per unit flow rate through each post-treatment step. However, none of these post-treatment area ratios can be of any service in detecting operational, sampling or analytical errors. These may have been present in some degree, and while the arbitrary omission of apparently aberrant data from some weekly sets might have improved the consistency of some ratios, the practice has been avoided in all, except a very few, instances. It seemed more informative to let the observed data stand on their own merits as indicative of what might "normally" be expected from in-plant, rather than laboratory or research type, operations.

Summary and Remarks on Post-Treatment

When the performance of one secondary post-treatment unit is pitted against that of another, more questions often arise than are answered. Some example questions may be, "Was the appropriate polymer used at the optimal concentration?" or "Should the filters be backflushed at regular, frequent intervals or when differential pressure across a unit demands a backflush?" or even "How often was the D.E. pre-coating successful?" These and other questions should be kept in mind reading this summary section.

The following categorical evaluation should give an impression of the efficiencies of the post secondary effluent processes.

Major effects of alum coagulation and polymer injection on secondary effluent:

1. Acidity increased about 25 per cent.
2. Alkalinity decreased about 15 per cent.
3. Dissolved C.O.D. decreased about 35 per cent.
4. Total C.O.D. decreased about 40 per cent.
5. Nitrate nitrogen decreased about 35 per cent.
6. Ortho-phosphate decreased about 40 per cent.
7. Total dissolved solids decreased about 8 per cent.
8. Sulfate increased about 15 per cent.
9. Suspended solids decreased about 17 per cent with a range between a 30 per cent increase and a 50 per cent decrease.
10. Turbidity decreased about 50 per cent.

Major effects of sand filtration on untreated secondary effluent:

1. Total C.O.D. decreased about 20 per cent.
2. Turbidity decreased about 50 per cent.
3. Suspended solids decreased about 50 per cent.

Major effects of sand filtration on coagulated reactor-clarified secondary effluent:

1. Dissolved C.O.D. decreased about 15 per cent.
2. Total C.O.D. decreased about 15 per cent.
3. Turbidity decreased about 55 per cent.
4. Suspended solids decreased about 60 per cent.

Major effects of activated carbon filtration on reactor-clarified, sand filtered secondary effluent:

1. Dissolved C.O.D. decreased about 70 per cent.
2. Nitrate nitrogen decreased about 45 per cent.
3. Turbidity decreased about 80 per cent.
4. Suspended solids decreased about 90 per cent.

Major effects of activated carbon filtration of sand filtered (only) secondary effluent:

1. Total and dissolved C.O.D. decreased about 75 per cent.
2. Turbidity and suspended solids decreased about 90 per cent.

Major effect of D.E. filtration on reactor-clarified, sand and activated carbon filtered secondary effluent:

1. Residual detectable suspended solids (1 mg/l) removed (100 per cent reduction).

Reactor-Clarification vs. Sand Filtration

The performance of the reactor-clarifier was generally satisfactory. Influent C.O.D. of which 75 per cent was soluble, was reduced by 40 per cent. The dissolved organic removal could be due to adsorption on the alum floc and/or biological reactions. The B.O.D. concentration in the secondary effluent averaged around 26 mg/l (Table 3) and the low overflow rate of 0.55 gpm/sq. ft. and 2.4 hr detention time is sufficient for biological reactions. Biological activity (despite the chlorination of secondary effluent from March, 1970 to November, 1970) is also shown by the 35 per cent decrease in nitrate-nitrogen which is probably due to denitrification. Sand filtration was capable of 20 per cent C.O.D. reduction, due to the removal of particulate C.O.D.

which is close to the 25 per cent particulate C.O.D. removed by alum/polymer clarification. Alum (polyelectrolyte) clarification had three advantages over sand filtration: (a) removal of colloidal and some organic materials, (b) removal of phosphate, about 40 per cent due to the aluminum phosphate chemical reactions, and (c) reduction of pH to reduce both membrane hydrolysis and precipitation of chemical compounds. Sand filtration showed a greater capability of removing suspended solids as compared to the reactor-clarifier treatment (50 vs 17 per cent). This is probably due to biological reactions in the clarifier which releases gases, making it difficult to maintain the sludge blanket thereby causing floc to float and discharge with the effluent. A negative aspect of reactor-clarification is the high cost as compared to sand filtration.

Sand Filtration vs. Granular Activated Carbon Filtration:

Granular activated carbon filtration was used to remove dissolved organics and particulate matter. Granular activated carbon treatment resulted in 70 per cent dissolved C.O.D. removal, 45 per cent nitrate nitrogen removal (probably due to denitrification), a turbidity decrease of 80 per cent and suspended solids decrease of about 90 per cent. Sand filtration on untreated secondary effluent resulted in 20 per cent C.O.D. removal, turbidity reduction of 50 per cent and suspended solids decrease of 50 per cent. The advantage of granular activated carbon treatment is the greater removal of constituents from secondary effluents that can cause membrane fouling. The disadvantage of activated carbon treatment is the higher costs as compared to sand filtration.

D.E. Filtration

D.E. filtration appears to offer little advantage as a polishing filter if sand filtration or the granular activated carbon filter is used prior. The higher cost of D.E. filtration and the apparently slight benefits derived as a polishing filter makes its use of questionable value.

In conclusion, it appears that substantial refractory reduction is feasible using three of the four post-secondary treatment processes. They are: alum reactor-clarification, sand filtration and granular activated carbon filtration. It is difficult to form generalizations from the tabulated data but it seems valid to infer from the data that if full treatment (reactor-clarification, sand filtration and granular activated carbon) is scaled at unity, lesser degrees of post-secondary effluent treatment would have roughly the following ratios of solute removal:

Sand filtration and granular activated carbon filtration	0.90 to 0.95
Reactor-clarification and sand filtration	0.70 to 0.80
Sand filtration only	0.50 to 0.60

One other combination not tested during this project was reactor-clarification followed by granular activated carbon. Operating cost of this combination,however, is predictably higher (1) because of normal carbon expense and (2) rapid carbon fouling caused by alum carry-over.

SECTION VIII

REVERSE OSMOSIS OPERATIONS - PRELIMINARY DISCUSSION

Introduction

Although "Reverse Osmosis" is already a familiar term in the water works field, there are presumably many who have a limited knowledge of the process. It is fortunate, however, that there are numerous sources now available describing reverse osmosis in various degrees of detail. For this reason the process theory will not be discussed in this report. An excellent introductory article appears in the August 31, 1972 "Reference Number" issue of Water and Sewage Works. For greater detail, books by Merten or Souririjan should be helpful.

Most attention during this study was centered around the comparative performance characteristics (flux rate, configuration influence, membrane life, etc.) of commercially available R.O. (reverse osmosis) units. The various feed conditions (already described) provided the means to gain broad information of R.O. unit capabilities. Inspection of individual unit performance using specific feeds was the means of determining the range of limitations for each unit.

Sections IX through XIV describe individual unit capabilities and characteristics, while Sections XV and XVI present the performance and cost comparisons.

Equipment and Facilities

Five reverse osmosis units were connected in parallel to a feed manifold permitting the entire group to receive the same feed or any fraction of the group to be supplied with a feed from any other point of the post-treatment sequence.

Each reverse osmosis unit had its own feed pump, pH control and sulfuric acid make-up system, piping, valves, instruments and sampling points. Figure 6 is a generalized process and instrument diagram applicable to all units. Of course, there were slight differences between units; Figure 7 shows a particular arrangement of a reverse osmosis unit installation.(Universal).

Initially, brine and product waters from each unit were returned to the terminal secondary effluent flume of the sewage treatment plant. Later, in keeping with the basic project purpose (of salt removal), these brines were sent to the District Salt Evaporation Pond. No problems with the brine disposal pond were recorded since the pond operated substantially below design capacity. Originally, the pond was constructed to accomodate all water softener regeneration brines which would otherwise be discharged into the sewage collection system.

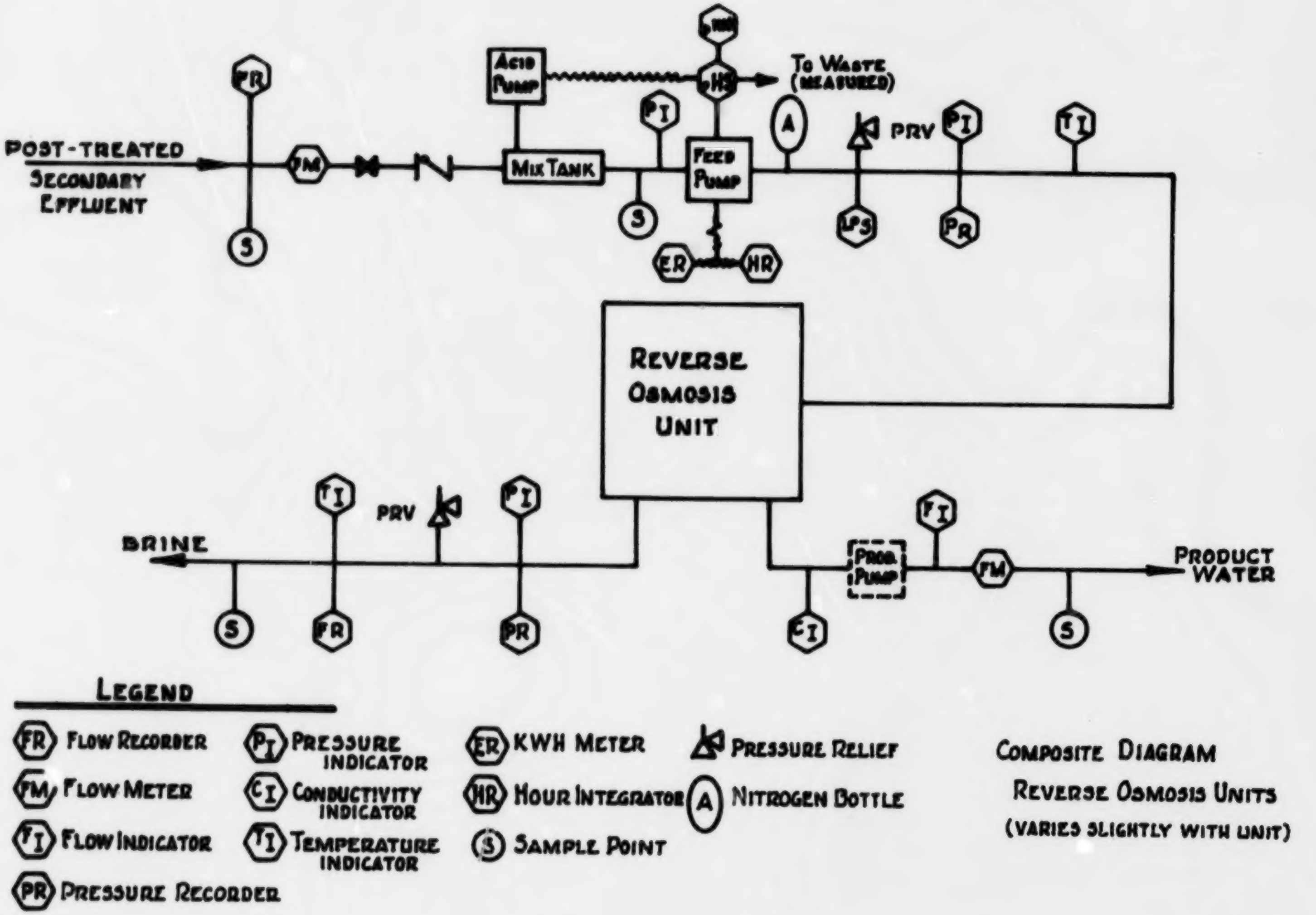

POST-TREATED SECONDARY EFFLUENT
FR
S
FM
ACID PUMP
MIX TANK
PI
S
pHS
TO WASTE (MEASURED)
FEED PUMP
ER
HR
A
PRV
LPS
PI
PR
TI
REVERSE OSMOSIS UNIT
BRINE
S
TI
FR
PRV
PI
PR
CI
PROD. PUMP
FI
FM
S
PRODUCT WATER
LEGEND
FR FLOW RECORDER
FM FLOW METER
FI FLOW INDICATOR
PR PRESSURE RECORDER
PI PRESSURE INDICATOR
CI CONDUCTIVITY INDICATOR
TI TEMPERATURE INDICATOR
ER KWH METER
HR HOUR INTEGRATOR
S SAMPLE POINT
PRESSURE RELIEF
A NITROGEN BOTTLE
COMPOSITE DIAGRAM
REVERSE OSMOSIS UNITS
(VARIES SLIGHTLY WITH UNIT)

Figure 6. Generalized reverse osmosis unit flow scheme

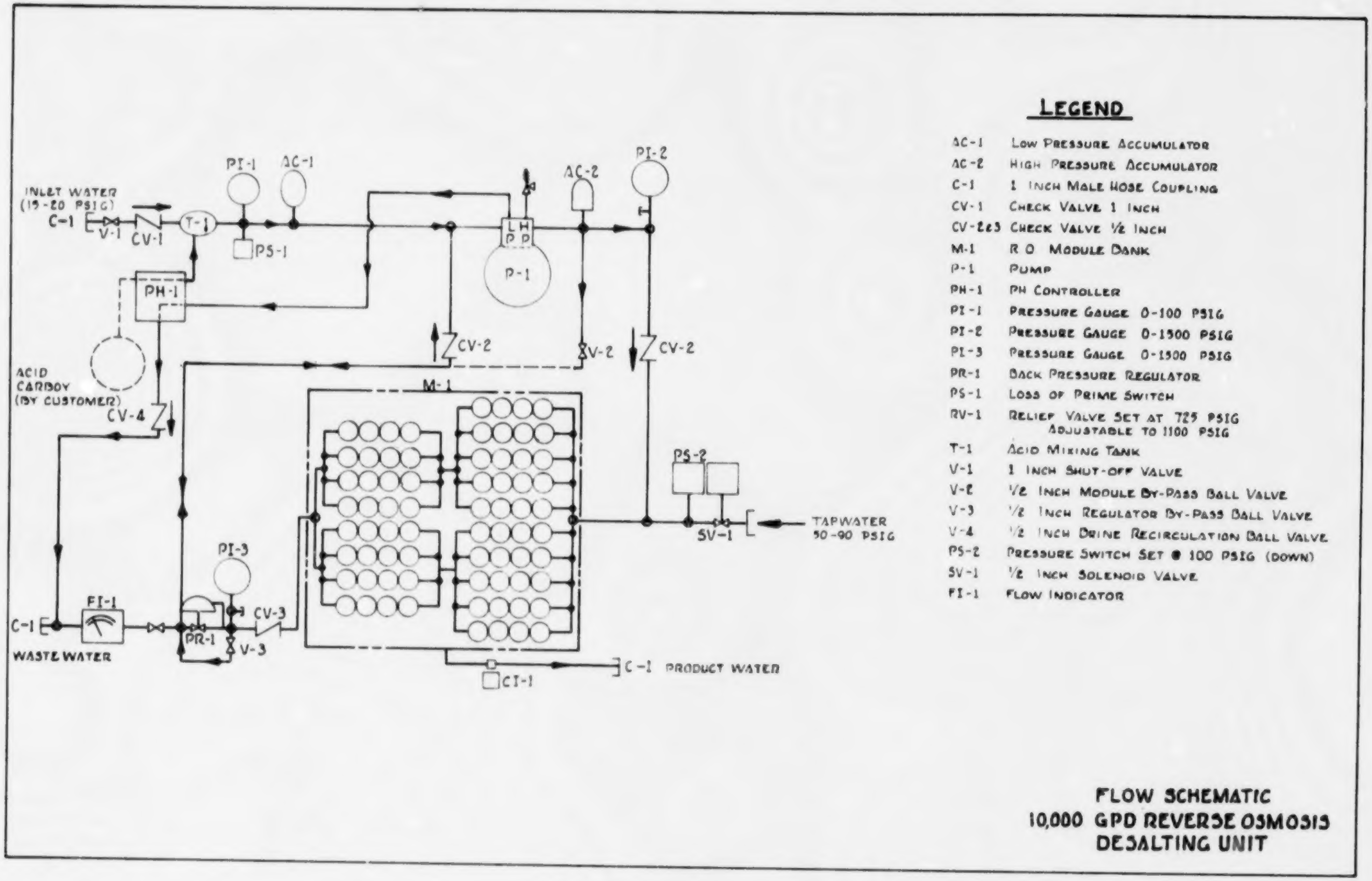

INLET WATER (15-20 PSIG)
C-1
V-1
CV-1
T-1
PI-1
AC-1
PS-1
PH-1
ACID CARBOY (BY CUSTOMER)
CV-4
CV-2
M-1
L H
P P
P-1
AC-2
PI-2
V-2
CV-2
PS-2
SV-1
TAPWATER 50-90 PSIG
PI-3
CV-3
PR-1
V-3
FI-1
C-1
WASTE WATER
CI-1
C-1 PRODUCT WATER
LEGEND
AC-1 Low Pressure Accumulator
AC-2 High Pressure Accumulator
C-1 1 Inch Male Hose Coupling
CV-1 Check Valve 1 Inch
CV-2&3 Check Valve ½ Inch
M-1 R O Module Bank
P-1 Pump
PH-1 PH Controller
PI-1 Pressure Gauge 0-100 PSIG
PI-2 Pressure Gauge 0-1500 PSIG
PI-3 Pressure Gauge 0-1500 PSIG
PR-1 Back Pressure Regulator
PS-1 Loss of Prime Switch
RV-1 Relief Valve Set at 725 PSIG Adjustable to 1100 PSIG
T-1 Acid Mixing Tank
V-1 1 Inch Shut-off Valve
V-2 ½ Inch Module By-Pass Ball Valve
V-3 ½ Inch Regulator By-Pass Ball Valve
V-4 ½ Inch Brine Recirculation Ball Valve
PS-2 Pressure Switch Set @ 100 PSIG (DOWN)
SV-1 ½ Inch Solenoid Valve
FI-1 Flow Indicator
FLOW SCHEMATIC
10,000 GPD REVERSE OSMOSIS
DESALTING UNIT

Figure 7. Flow schematic, 10,000 gallon per day R.O. unit (Courtesy Universal Water Corp.)

Operational Control

All units operated twenty-four hours a day, seven days a week whenever possible, and were under the control of one technician ten hours per day, five days a week. Although the units were unattended at night and on weekends, considerable overtime was required. The remainder of the crew consisted of two chemists and an equipment operator for the post-secondary treatment area.

Operating data were collected from each R.O. unit by making careful instrument readings at least once each working day. These were supplemented by near-hourly observations of the various indicating and recording instruments, a practice used to detect abnormalities of operation.

These data were recorded on key-punch data input sheets for processing on the IBM 1130 computer. The computer printout consisted of "daily" and "monthly" summary reports, both of which included raw data, various ratios (e.g. - water recovery and rejection), ambient temperature flux rates, A values, plus a limited amount of chemical analytical data and operational comments. Over a thousand of these printout sheets were generated during the experimental phase of the project. A copy of a specimen daily printout is shown in Table 14 while the monthly printouts can be found in the Appendix. As mentioned earlier, the algebraic formula used in computing the various ratios and correction factors are also found in the Section "Appendices." Though the computed ratios were adequate for daily control and short term process evaluation, it eventually became evident that methods for cross-correlating data and computed ratios would be needed if incongruities of the data were to be detected. Using various derived equations (Appendix A-1) additional computer programs were written to develop more useful information and to provide other indices of performance.

pH Control

At this time it seems appropriate to mention pH control of the unit feeds as it cannot be classified as a membrane cleansing agent per se, nor is it fitting to include it as a secondary post-treatment since it was never removed during the experimental work phase. The evidence for making pH control a requirement is substantial. In 1957 Breton (E.J.) published his findings which indicated a correlation between feed pH and membrane longevity. From this, pH control was assumed to control the rate of some chemical reaction associated with membrane molecular structure. Breton submitted that this reaction was the hydrolysis of cellulose acetate, an ester. This view was reinforced when Vos, Burris and Riley derived a rate constant for the reaction based on their own experimental evidence. Being pH dependent, the constant reaches a minimum between pH 4.5 and 5.0, well on the acid side (see Merten, p. 151). pH control in the acid direction also retards scale formation.

Table 14. DAILY COMPUTER PRINTOUT

```
EASTERN MUNICIPAL WATER DISTRICT                                                 REVERSE OSMOSIS TEST

DAILY STATISTICS DETAIL                               RAW DATA                   FOR SEP  9, 1970

                                   AEROJET AMER.STND.   DU PONT  GULF G.A.  UNIVERSAL
***PHYSICAL DATA***

FEED FLOW, TOTAL                      0.00       9.15       8.75       8.95       9.95         GPM
          PH SENSOR                   0.00       0.15       0.20       0.20       0.10         GPM
          TO DRAIN                    0.00       0.30       0.35       0.00       0.00         GPM
          NET, UNADJUSTED             0.00       8.70       8.20       8.75       9.85         GPM

     PRESSURE                            0        600        630        600        640         PSI
     CONDUCTIVITY, UNADJ.                0       1450       1450       1430       1460MICROMHOS/CM
       DETERMINED AT                     0         82         85         86         87      DEG.F.
     TEMPERATURE IN LINE                 0         82         86         92         87      DEG.F.

BRINE FLOW, BY DIFFERENCE             0.00       2.15       1.90       2.75       5.40         GPM

     PRESSURE                            0        400        495        595        600         PSI
     CONDUCTIVITY                        0       4950       3850       4400       1930MICROMHOS/CM
       DETERMINED AT                     0         84         88         93         89      DEG.F.
     TEMPERATURE IN LINE                 C         83         88         93         90      DEG.F.

PRODUCT FLOW                          0.00       6.55       6.30       6.00       4.45         GPM
     CONDUCTIVITY, UNADJ.                C        345        635        130        960MICROMHOS/CM
       DETERMINED AT                     0         82         87         92         88      DEG.F.

PH FEED, RAW                          0.00       7.20       7.35       7.00       7.00
   FEED, POST-ACID                    0.00       4.25       5.70       5.00       5.60
   BRINE                              0.00       3.55       5.75       5.15       5.65
   PRODUCT                            0.00       4.80       5.55       5.35       5.60

MEMBRANE AREA                          0.0      791.7   160900.0      900.0      224.0      SQ.FT.
FEED METER READING                      0.     63440.    681840.    456940.    940300.     GALLONS
PRODUCT METER READING                   0.    785650.    349090.    872780.    173230.     GALLONS
ELECTRIC POWER METER                    0.      7522.     12448.      1018.     17910.         KWH
TEST HOURS ACCUMULATED                 0.0     2333.3     3697.7     4358.4      852.9       HOURS
OFF TIME (TODAY)                        0.         4.         0.         0.         0.       HOURS
TIME DATA TAKEN                          0        945       1530       1450       1510       HOURS
PRETREATMENT CODE                        0         31         23         23         31

TREATMENT, KIND                       NONE       NONE       NONE       NONE       NONE
           START TIME                    0          0          0          0          0
           END   TIME                    0          0          0          0          0
           LENGTH                        0          0          0          0          0

***ANALYTICAL DATA***

TOTAL DISS.SOLIDS, FEED                           710        705        705        710         PPM
                   BRINE                         2805       2505       2530       1080         PPM
                   PRODUCT                        225        285         40        440         PPM
TURBIDITY          FEED                                                                     J.T.U.
                   PRODUCT                                                                  J.T.U.
TOTAL CHEM.OX.DEM. FEED                                                                        PPM
                   PRODUCT                                                                     PPM
DISS. CHEM.OX.DEM. FEED                                                                        PPM
                   PRODUCT                                                                     PPM
CHLORINE           FEED                            .8         .8         .8         .8         PPM
                   PRODUCT                                                                     PPM
AMMONIA NITROGEN   FEED                                                                        PPM
                   PRODUCT                                                                     PPM
NITRATE NITROGEN   FEED                            .0         .0         .0         .0         PPM
                   PRODUCT                         .0         .0         .0         .0         PPM
TOTAL PHOSPHORUS   FEED                           6.6        6.6        6.6        6.6         PPM
                   PRODUCT                        1.3        2.3         .1        3.9         PPM
***COMMENTS***

AMER.STD. OFF 4 HRS PUMP REPAIR.  RUPTURED MODULE 1435 - BYPASSED. (CHANGED OIL)

***PERFORMANCE INDICES, CORRECTED FOR TEMPERATURE***

RECOVERY               R          0.00      69.35      66.27      53.59      98.33   PER CENT
REJECTION, TOTAL       J          0.00      76.20      57.13      91.49      34.96   PER CENT
REJECTION, AVERAGE     K          0.00      89.04      75.99      95.57      43.27   PER CENT

WATER FLUX             F    0.00000000 0.00762106 0.00003377 0.00521092 0.01685708 GPM/SQ.FT.
WATER FLUX             F        0.0000    10.9743     0.0486     7.5037    24.2741 GPD/SQ.FT.
WATER FLUX             F    0.00000000 5.17549802 0.02293634 3.5387568511.44771006 GMS/SQM*SEC

A VALUE                A    0.00000000 0.15972073 0.00061441 0.08982336 0.27335041 G/SM*SEC*AT
```

One scaling agent, calcium carbonate, does not exist below pH 5.0 as a result of removing carbonate alkalinity. Another, calcium phosphate, rapidly increases its solubility at pH's below 6.0. In spite of pH control shown in Table 15, membrane fouling by scaling still occurred. Except for short periods of no pH control (malfunctioning acid pumps)the pH was nearly always within the limits recommended by the manufacturer.

Membrane Fouling and Cleansing

It is believed that at least two, and perhaps three types of membrane fouling occurred during the operations. A calcium deposit chemically identified as tri-calcium orthophosphate was found in membranes of the American Standard unit about Week 23. Similar deposits were later found in other units. These deposits could be removed by a 15,000 to 30,000 ppm (2 to 4 oz./gal.) solution of EDTA (Questex 4SW or Versene 100) in water, adjusted to a pH of 7 with sulfuric acid. Solutions of pH 3 to 4 sulfuric acid also effected various degrees of permeation improvement but this was probably due to calcium carbonate removal. Chemically, the calcium carbonate could have occurred solitarily, bonded to phosphate or both.

Organic slime also contributed to membrane fouling but a 15,000 ppm (2 oz./gal.) solution of "BIZ", an enzymatic-detergent by Proctor and Gamble, seemed moderately effective in the removal of slimes as there was usually a marked improvement in product flux following a "BIZ" soaking. After the carbon and sand filter treatments were removed, a portion of this slime film, (assumed to be also on the other units) was removed from a Universal unit module for analyses.

When placed in water, the slime material appeared to consolidate into an amorphous gel; the filmy appearance returned when separated from the water. Samples of the film were sent to most of the R.O. equipment suppliers, and one commented on the material:

> "...The foulant was very slimy and brown colored. (It was a light tan). The appearance at 1000X (magnification) was that of a typical membrane deposit from a unit running on polluted surface waters. The deposit appeared to be composed of (an) aggregation of colloidal and particulate solids held together in a biologically oriented slime matrix. Present in the sample were large masses of a filamentous fungi and large numbers of a rod shaped (10 by 20µ) bacteria... There was no obvious life in the sample but (it was felt) that the bacteria seen grew in situ and were not trapped or deposited in large numbers from the feed water...More than 0.5 ppm of residual chlorine are (probably) required to prevent biological growth in sewage effluents..."

Figures 8 and 9 show two microphotographs made by Gulf General Atomic at high magnification. The large groups of bacteria were difficult to record photographically (without drying and staining) because of Brownian motion.

Table 15. RECORD OF R.O. UNIT FEED pH

Period Covered Week Nos.	Post-Treatment Sequence (A=Reactor-Clarifier) (B=Sand Filters) (C=Carbon Filters) (D=D.E. Filters) (E=Pre-R.O. Unit Chlorination) (F=pH Control)	Reverse Osmosis Manufacturer	Average pH
2-7	A,B,C,E,F	Aerojet	5.82
5-7	A,B,C,E,F	Du Pont	5.52
1-7	A,B,C,E,F	Gulf	5.62
1-7	A,B,C,E,F	Universal	5.71
7-17	A,B,C,D,E,F	Aerojet	5.67
14-28	A,B,C,D,E,F	American Standard	4.64
7-24	A,B,C,D,E,F	Du Pont	5.69
7-24	A,B,C,D,E,F	Gulf	5.51
7-30	A,B,C,D,E,F	Universal	5.66
28-33	A,B,C,E,F	American Standard	4.77
24-33	A,B,C,E,F	Du Pont	5.45
24-33	A,B,C,E,F	Gulf	5.38
31-33	A,B,C,E,F	Universal	5.63
35-36	B,C,E,F	Aerojet	5.77
34-41	B,C,E,F	American Standard	-
34-38	B,C,E,F	Du Pont	5.33
38-41	B,C,E,F	Du Pont	6.11
33-41	B,C,E,F	Gulf	5.49
33-41	B,C,E,F	Universal	5.67
41-47	A,B,C,E,F	American Standard	5.14
41-49	A,B,C,E,F	Du Pont	5.91
41-46	A,B,C,E,F	Gulf	5.42
41-48	A,B,C,E,F	Universal	5.54
49-53	A,B,E,F	Du Pont	5.77
46-57	A,B,E,F	Gulf	5.23
48-57	A,B,E,C	Universal	5.65
61-64	B,E,F	American Standard	5.54
57-64	B,E,F	Du Pont	5.57
57-66	B,E,F	Gulf	5.49
62-64	B,E	Raypak	7.45
57-64	B,E,F	Universal	5.70
64-69	E,F	American Standard	5.01
64-66	E,F	Du Pont	5.66
66-69	E,F	Gulf	5.55
64-68	E	Raypak	7.46
64-69	E,F	Universal	5.78

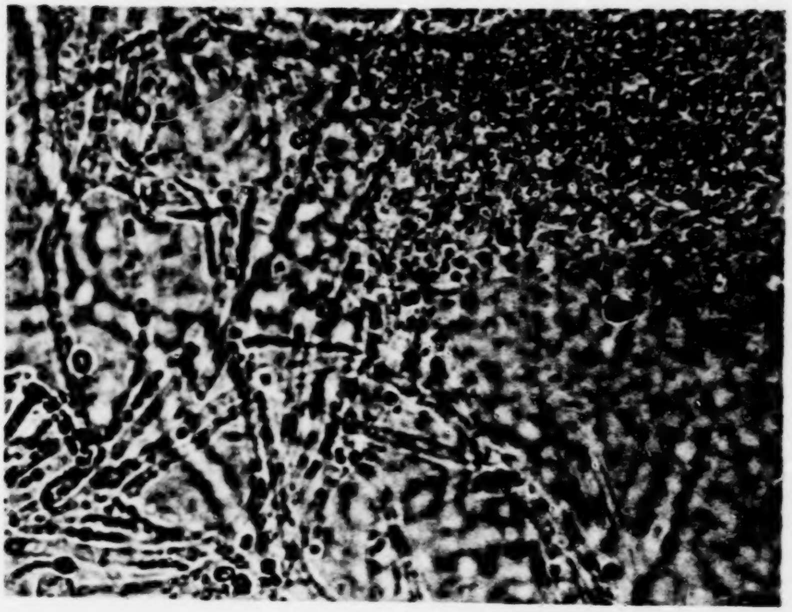


Figure 8. Microphotograph of slime removed from Universal R.O. unit (Courtesy, Gulf)

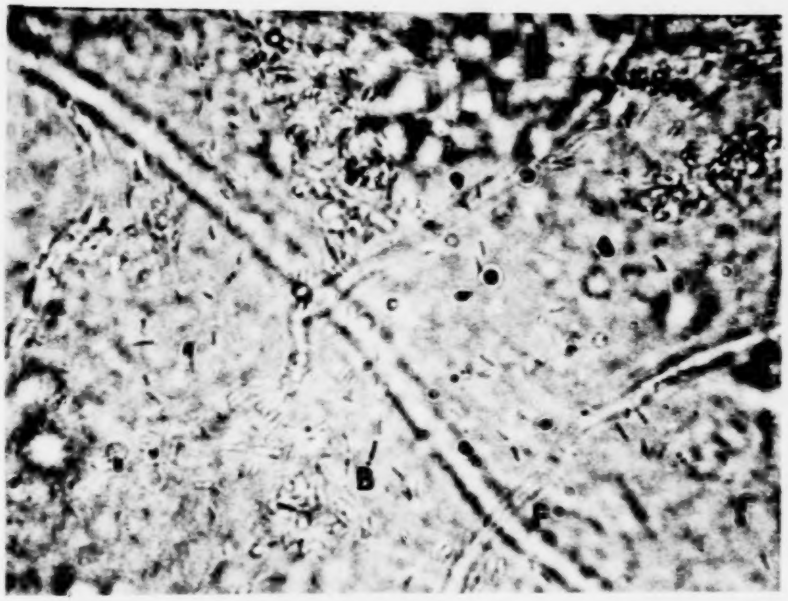


Figure 9. Slime microphotograph (Courtesy, Gulf); B=bacteria, F=fungus, S=particulate solids

Another form of fouling was particulate solids deposition. Exactly when these deposits began to substantially affect membrane flux is uncertain. For the most part the buildup was gradual except when a post-secondary effluent treatment process was removed. By the time untreated secondary effluent was being fed to the units, particulate solids were probably the chief fouling agents. Evidence of particulate fouling is graphically shown in the project report by Aerojet-General Reverse Osmosis Renovation of Municipal Wastewater, (contract 14-40-184) page 140. The fouling depicted is probably a good representation of membrane fouling as it occurred at Hemet. In light of the potential for particulate solids fouling, one manufacturer (Du Pont) insisted that the feed flow to their unit be passed first through Cuno filters (See Section XI).

In addition to EDTA and BIZ, a number of other types of membrane cleansing and flushing solutions were used, particularly during the latter phases of the project when the feed quality had deteriorated considerably due to the removal of post-treatment processes. All cleansing solutions were used with the knowledge and consent of the R.O. manufacturers. A number of weak acid solutions (pH 3 to 5) were used some of which were sulfuric, phosphoric, sulfamic and hydrochloric. Additionally, solutions of sodium perborate with Tritox-100, carboxymethyl cellulose, and sodium hypochlorite were tested. Cleansing effects are generally discussed in the particular unit sections (IX through XIV) while copies of flushing data sheets appear in Appendix Section A-3.

The rate of membrane fouling plus the frequency and effectiveness of the cleansing methods employed are factors which must be considered to evaluate the reverse osmosis units. The usual procedure, in this project was to flush a unit whenever the flux rate dropped to 85 or 90 per cent of the initial rate. Consequently, the operating periods for the R.O. units varied from several days to many weeks, depending upon the feed conditions, membrane fouling susceptibility,flushing history, etc. In the latter stages of the project, an attempt was made to determine optimum flushing time more objectively by a mathematical approach using Equation (6). Membrane fouling is considered to be inevitable when using a high solute feed such as the treated and untreated effluent used in this study. There were, however, two partially controllable factors which may have increased the rate of fouling: 1) variation of Reynolds numbers stemming from changes in basic flow patterns, and 2) the low levels of pre-R.O. unit chlorination (less than 0.5 ppm residual) necessary to accomodate the Du Pont nylon filament permeators. While none of the manufacturers seemed to feel that low chlorine residuals would adversely effect the performance of their equipment, it is possible that some were not then thinking in terms of a gradually deteriorating feed quality.

Reynolds Numbers

It was not a part of this project to research the theoretical aspects of reverse osmosis, but the role of Reynolds Numbers as encountered requires some consideration. Reynolds Number is dimensionless as shown in the equation below (Goel and McCutchan, October, 1971).

$$N_{re} = \frac{V_b \text{ X } D}{v}$$

where:
N_{re} = Reynolds Number (Dimensionless)
D = Diameter of tube (ft.)
v = kinematic viscosity ($1.039 \text{ X } 10^{-5}$ ft.^{2}/sec) determined experimentally
V_b = brine velocity (ft./sec.)

Because V_b (velocity) $= \frac{Q \text{ (volume as ft}^3\text{/sec)}}{A \text{ (area of tube in ft}^2}$, the N_{re} equation can be expressed in terms of volume rate (gpm). Combining all factors, the expression becomes:

N_{re} = 3284 Q/d
where d = tube diameter (inches) and
Q and d are unique for each calculation

The Reynolds Number is important as an indicator of turbulence within the membraned tube. The effect of increasing the flow rate is to increase the Reynolds Number but the rate can be increased only to the extent that it doesn't cause a detrimental pressure drop across the R.O. unit. By reducing the flow rate and thereby the Reynolds Number, the rate of fouling may increase. In addition, water recovery and solute rejection may be affected adversely.

It was possible, with some degree of confidence, to estimate the Reynolds Numbers for the Aerojet-General, Raypak and Universal R.O. units which had relatively uniform geometric properties. The Reynolds Numbers for the American Standard unit, with its internal spherical "turbulence promotors", and the Du Pont and Gulf units, with their intricate internal flow patterns, could only be examined through some analog function such as the frictional energy loss per unit length of module, etc.

A communication from Abcor, with regard to the American Standard unit (the Conseps division of American Standard, the R.O. unit manufacturer was acquired by Abcor December 20, 1970) reads in part as follows:

> "... In a tube with turbulence promotor spheres, turbulence is not equally distributed so we are dealing with an average Reynolds Number... Based on an idea that the same amount of energy loss per length of tube means the same amount of turbulence (as implied by the Reynolds Number) an equivalent or apparent N_{Re} can be established for a tube with T.P. (Turbulence Promotors)..." Example:
> TM 5-14 with T.P.
> at 0.24 gpm pressure drop is 22 psi - energy loss
> 0.25 x 22 = 5.5 gpm psi = 2.5 watts
> TM 5-14 without T.P.
> at 0.7 gpm pressure drop is 8 psi - energy loss
> 0.7 x 8 = 5.6 gpm psi"

> "... This means 0.25 gpm with T.P. is approximately equal to 0.7 gpm without T.P., the latter representing a Reynolds number of approximately 3500..."

Reynolds Numbers for the tubular units (Aerojet-General and Universal) and the annular spaced Raypak unit were estimated from the feed and product flow rates, by using the modified Reynolds Number expression, after making some simplifying assumptions:

1. The kinematic viscosity (determined from brine density and absolute viscosity) of the exit modular flows was essentially constant regardless of the section location.
2. The parasitic head losses and induced turbulence in the inter-unit piping and return bends, etc. were negligible;
3. The product permeation rate in gal./sq. ft.-min. was constant regardless of the module position. (This implies a constant net effective operating pressure throughout the unit and the absence of localized internal fouling, obstructions, etc.);
4. No tubes or modules were out of service.

Example:

Flow pattern "a" (Figure 10) for the Aerojet unit was an arrangement of six modules in parallel followed by four modules in parallel and terminated by two modules in parallel.

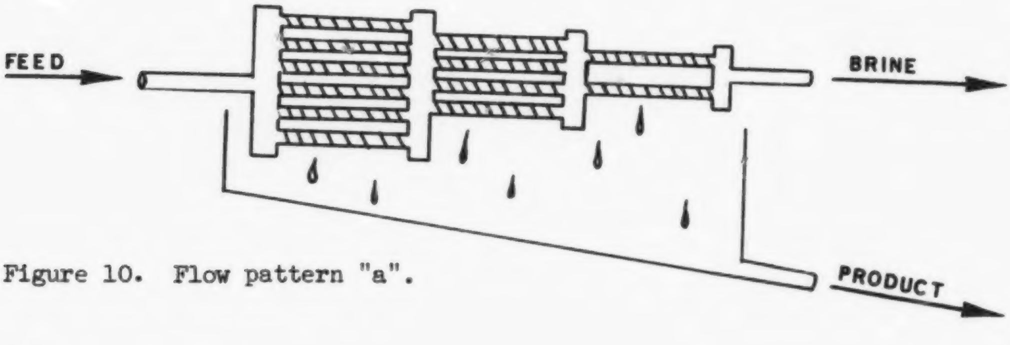


Figure 10. Flow pattern "a".

Let:

(f) = volume rate of total feed entering reverse osmosis unit (gpm).

(p) = volume rate of total product leaving reverse osmosis unit (gpm).

Each module contained 16 - 9/16" inside diameter tubes in series. Feed rate (f) was 7.25 gpm and the product rate (p) was 2.25 gpm. The brine flow rate for each section of parallel modules was then calculated:

First section: $(f/6) - (p/12) = 1.021 \text{ gpm} = Q_1$

Second section: $(6\,Q_1/4) - (p/12) = 1.344 \text{ gpm} = Q_2$

Third section: $(4Q_2/2) - (p/12) = 2.500 \text{ gpm} = Q_3$

In this case d = 0.5625 in. and $N_{re} = 5840Q$. Since there are maximum and minimum brine flows within each section, three values of N_{re} per modular section are given below:

Table 16. AEROJET-GENERAL REYNOLDS NUMBERS

	Max. N_{re}	Min. N_{re}	Avg. N_{re}
First Section	7,060	5,960	6,510
Second Section	8,940	7,850	8,390
Third Section	15,700	14,600	15,150

The critical minimum Reynolds values for the R.O. units have been summarized in Table 17 according to flow patterns. In the case of Raypak, the hydraulic radius rather than the actual tube diameter was used in computing the value.

Turbulet flow conditions are usually present when the average Reynolds Number is above 3,000 or 4,000, but concentration polarization problems may still occur in the last tube section while operating in this range. An average lower limit of about 5,000 is probably desirable for most reverse osmosis operations.

Although it is possible that some other dimensionless grouping, such as the Schmidt or Prandtl Numbers might have had more significance than the Reynolds Number, they were not investigated.

Data Reduction

Section V discusses the major aspects of the computational methods used in this report. It is now desirable, in anticipation of the presentation of the summary data sheets for the individual reverse osmosis units in Sections IX to XIV, to discuss and give a few examples of the IBM 1130 computer output sheets from which the summary information was derived.

Various programs were written for the study of the reverse osmosis water permeability and rejection data. Each had a number of auxiliary programs developed for special purposes. Some examples of final program print-outs are shown in Tables 14, 18, 19, 20 and in Appendix A-6.

Table 17. ESTIMATED MINIMUM REYNOLDS NUMBERS PER MODULAR SECTION

Unit	Flow Pattern	Data Date	Estimated Reynolds Number			
			Section			
			I.	II.	III.	IV.
Aerojet General	a	5/6/70	5,970	7,870	15,000	
	b	5/22/70	3,970	3,450	5,370	
	c	10/28/70	5,200	5,060	9,150	
	d	11/4/70	10,450	12,800	22,600	19,200
Raypak	o	5/11/71	6,950			
Universal	p	5/6/70	4,100	1,850	1,250	
	q	9/1/70	9,750			
	r	9/28/70	10,400	15,100		
	s	12/18/70	8,100			

Table 13. PROGRAM OUTPUT, "WATER PERMEABILITY STUDIES"

```
UNIT       RUN        FROM     THROUGH    EXCLUDING

DUPT      DPU6   11/18/70   12/07/70

    DATE  ALC.HRS      HOURS     A VALUE           X           Y          XX          XY          YY

11/18/70      4.0        1.0  0.3553912    0.000000   -0.449293    0.000000    0.000000    0.201864
11/19/70     22.7       19.7  0.3408401    1.294466   -0.467449    1.675641   -0.605096    0.218508
11/20/70     45.9       42.9  0.3135730    1.632457   -0.503661    2.664915   -[illegible].822205    0.253674
11/23/70    119.4      116.4  0.3191512    2.065952   -0.496003    4.268158   -1[illegible]24719    0.246019
11/24/70    145.0      142.0  0.3167549    2.152287   -0.499276    4.632342   -1.[illegible]4586    0.249276
11/25/70    164.1      161.1  0.3152807    2.207095   -0.501302    4.871267   -1.[illegible]422    0.251304
11/27/70    210.1      207.1  0.3056597    2.316179   -0.514761    5.364686   -1.1[illegible]80    0.264979
11/30/70    272.0      269.0  0.2847167    2.429751   -0.545586    5.903692   -1.32[illegible]    0.297665
12/01/70    293.4      290.4  0.2837620    2.462996   -0.547045    6.066349   -1.3473[illegible]    0.299258
12/02/70    324.7      321.7  0.2768708    2.507450   -0.557722    6.287306   -1.398461    0.311054
12/03/70    343.1      340.1  0.2741742    2.531606   -0.561973    6.409028   -1.422694    0.315814
12/04/70    366.4      363.4  0.2714952    2.560384   -0.566237    6.555567   -1.449786    0.320625
12/07/70    437.1      434.1  0.2703951    2.637589   -0.568001    6.956875   -1.498153    0.322625

TOTALS                        3.9280633   26.798210   -6.778312   61.655815  -14.267412    3.552669

MEANS                         0.3021587    2.061400   -0.521408

UNIT      RUN        FROM     THROUGH     AVG A VAL       SLOPE   INTERCEPT     STD DEV           T

DUPT      DPU6   11/18/70    12/07/70     0.3021587   -0.045930   -0.426728    0.008306   -5.529323
```

Table 19. PROGRAM OUTPUT, "AVERAGE REJECTION RATIOS"

```
GULF    91  WEEKS 49 THROUGH 69                                                                      STANDARD DEVIATIONS

ITEM       FEED     PRODUCT       BRINE REJECTION    RECOVERY EFFICIENCY NF NP NB NR NV NE REJECTION RECOVERY EFFIC'CY

RCHLDE   141.18       19.27      242.50     88.67       46.57      90.68 11 11 10 10 19 10    0.1425   0.1490   0.1250
RSCOND  1412.84      112.00     2584.42     94.32       46.57      94.80 19 19 19 19 19 19    0.0124   0.1490   0.0321
RSO4     364.67        4.47      760.50     99.42       46.57     102.33 15 15 10 10 19 10    0.0093   0.1490   0.1743
RTDS     821.88       63.13     1428.13     94.07       46.57      97.53 16 16 16 16 19 16    0.0409   0.1490   0.1210
RACIDY  194.666     128.653     184.444     29.46       46.57      92.94 15 15  9  9 19  9    0.1577   0.1490   0.2451

RALKY    36.542      12.236      52.333     57.15       46.57     148.36 12 14  6  5 19  5    0.2196   0.1490   0.9129
RT.COD   44.407       3.564      65.000     93.28       46.57      91.48 15 11  9  9 19  9    0.0895   0.1490   0.1701
RD.COD   28.600       1.625        .000       .00       46.57        .00  4  4  0  0 19  0    0.0000   0.1490   0.0000
RORG.N    2.950        .300       3.400     90.63       46.57      87.19  2  1  1  1 19  1    0.0000   0.1490   0.0000
RTHARD  228.529       3.029     424.615     98.93       46.57     101.42 17 17 13 13 19 13    0.0131   0.1490   0.0965

RNH3.N  13.7500       .6100     15.6000     95.84       46.57      84.54  2  2  2  2 19  2    0.0492   0.1490   0.0200
RNO3.N   5.4967      2.8033     10.1783     55.05       46.57     118.55  6  6  6  6 19  6    0.2040   0.1490   0.2902
RORTOP  10.3588       .2560     19.3066     98.10       46.57      98.21 17 15 15 15 19 15    0.0455   0.1490   0.0959
RTURB    3.6094       .4013       .0000       .00       46.57        .00 16 15  0  0 19  0    0.0000   0.1490   0.0000
RCAL     62.800        .727     130.000     99.60       46.57     101.46 15 15 10 10 19 10    0.0016   0.1490   0.0798
```

The form in which the data and calculated results appear in Table 18 requires a few comments. Again, it should be mentioned, Zeros indicate the absence of data, not the level of the constituent. The X and Y designations refer to the common logarithms of the hours and A values, respectively. Both the mean A values and the mean hours are the anti-logarithms of the means of the groups of the listed X's and Y's, while the average A is the mean of the original A values. The slope (b) and the standard deviation of the slope are defined by Equations (5) and (22) found in Appendix A-1. The "A value intercept" refers to Equation (2) and represents the statistically calculated value of A at hour "one", while the "intercept" is its common logarithm. After Equation (3) is used to calculate the probable value for A at 1,000 hours, the two points may be joined on a log-log plot to show the A vs hours regression line.

Tables 19 and 20 should be considered together as part of a paired set of reverse osmosis data and average rejection ratios. The latter shows all of the feed, product and brine specific conductivity data for the Gulf unit from weeks 2 to 69. The average rejection ratio J_a (in percent) shown in the fifth column was calculated using Equation (14) and the material balance ratio ("E" - or "Efficiency") in the last column by Equation (7).

Columns 2, 3 and 4 of Table 19 show the period average constituent level for weeks 49 through 69. The N-series of columns indicate the number of data points included in the period and refer respectively to the number of feed, product, brine, rejection, recovery and "efficiency" data sets included in the averages. The total rejection ratios (J_t) Equation (16), included in the unit discussions, were calculated from data similar to that of Table 20.

Table 20. AVERAGE REJECTION RATIOS SUMMARY OUTPUT

```
GULF   105   RSCOND

WEEK    FEED   PRODUCT    BRINE  REJECTION   RECOVERY EFFICIENCY

   1
   2   120[illegible]    131     2420      92.77      52.16     101.66
   3   1230      138     1937      91.29      42.81      94.87
   4   1311      120     2420      93.57      50.95      95.21
   5   1197       90     2007      94.38      45.63      94.59

   6   1262       84     1845      94.59      46.03      81.97
   7   1100       90     2019      94.23      58.33      81.26
   8   1133       84     1956      94.56      55.72      80.58
   9   1394      107     3110      95.25      57.73      98.74
  10   1377       98     3020      95.54      59.16      93.78

  11   1250       96     2760      95.21      59.78      93.40
  12   1299      101     3440      95.74      65.42      96.66
  13   1206       83     2640      95.90      62.30      93.07
  14   1460       84     3558      96.61      62.17      99.87
  15   1313       87     3203      96.15      61.57      97.83

  16   1383       98     4488      96.66      69.36     104.35
  17   1278       92     3536      96.18      67.05      95.99
  18   1199       89     3516      96.22      67.04     101.63
  19   1317       87     4175      96.83      70.58      97.93
  20   1242       92     4268      96.66      71.51     103.20

  21   1286      101     3566      95.84      68.71      92.16
  22   1280      120     4254      95.66      69.71     107.20
  23   1155      101     3830      95.95      68.88     109.22
  24   1463      131     5235      96.09      71.59     108.07
  25   1235      119     4109      95.55      71.68     101.13

  26   1179       93     3765      96.24      66.85     111.13
  27   1182      104     3939      95.94      68.61     110.64
  28   1239      101     3266      95.52      67.63      90.84
  29   1128       99     3383      95.61      72.22      89.65
  30   1151       90     3213      95.88      70.30      88.40

  31   1253      122     3647      95.02      70.90      91.60
  32   1367      147     4005      94.53      71.59      90.91
  33   1275      134     3119      93.90      65.16      92.08
  34   1373      131     3738      94.87      70.06      88.20
  35   1173      114     2787      94.24      63.80      92.21
```

```
GULF   105   RSCOND

WEEK    FEED   PRODUCT    BRINE  REJECTION   RECOVERY EFFICIENCY
  36   1238      140     2811      93.08      62.26      92.73
  37   1295      143     2765      92.96      63.24      85.47
  38   1331      152     3153      93.22      60.69      99.60
  39   1276      159     2804      92.20      61.19      93.16
  40   1143      143     2574      92.31      60.28      96.99

  41   1313      159     2750      92.17      57.06      96.88
  42   1158      129     2366      92.64      55.94      96.25
  43   1274      167     2489      91.12      54.66      95.75
  44   1253      159     2162      90.69      49.29      93.78
  45   1100      143     2388      91.80      59.90      94.84

  46   1218      158     2672      91.89      62.80      89.75
  47   1347      159     2232      91.11      49.05      90.21
  48   1319      168     2276      90.65      47.44      96.74
  49   1383      138     4818      95.55      76.03      91.09
  50   1559      138     5333      96.00      76.07      95.26

  51   1251      114     2687      94.21      59.04      93.36
  52   1274       74     2183      95.72      45.26      96.43
  53   1179       96     2423      94.67      55.17      96.62
  54   1230       93     2478      94.98      55.88      93.11
  55   1380      102     2687      94.98      54.11      93.35

  56   1236       90     2412      95.07      55.87      90.19
  57   1139       83     2099      94.87      52.15      91.98
  58   1133       84     2015      94.66      49.22      93.96
  59   1328       99     2039      94.12      39.87      95.30
  60   1247       90     2088      94.60      44.57      96.03

  61   1287       86     2216      95.09      46.00      96.05
  62   1236       80     1767      94.67      36.26      93.47
  63   1235      129     1646      91.04      25.23     102.29
  64
  65

  66   2025      171     2703      92.[illegible]      29.98      96.00
  67   1839      140     2451      93.47      25.30     101.49
  68   2033      168     2813      93.07      33.18      95.20
  69   1850      153     2246      92.53      27.64      90.13
AVERAGES 1302.17   116.16   2953.33      94.35      57.45      95.36

NO. ITEMS   66        66        66         66         66         66

SDV  105.95694  28.17903  854.10070    0.01690    0.12502    0.06193
```

SECTION IX

AEROJET-GENERAL CORPORATION REVERSE OSMOSIS UNIT

TUBULAR MEMBRANE DESIGN

Introduction

This unit was obtained on a monthly rental basis from the Environmental Systems Division of Aerojet-General Corporation of El Monte, California; the divisional name was later changed to Envirogenics Company. As originally installed, it was termed a "tight membrane" tubular type with a nominal capacity of about 8,000 gallons of product water per day with a 90% rejection factor.

Physical Configuration

The installed Aerojet-General reverse osmosis unit, shown in the photograph (Figure 11), consisted in part of 192 vertical tubes positioned over a product water collecting pan. Each tube was 9/16 in. I.D. by 14 ft. 3 in. long and was made up of an outer fiberglass sheath enclosing both the tubular membrane and its spirally wound paper cover. These tubes were arranged in series-connected groups of 16 each to form module sets, each with a total membrane area of 33.12 sq. ft. (2.07 sq. ft. per tube). The modules were connected in groups to form various flow patterns, which in turn produced various levels of performance. The Reynolds Numbers applicable to each of these configurations are listed in Section VIII.

The four flow patterns tested are described below using lower case letters to identify the pattern:

"a" - Six modules in parallel, followed in series by four modules in parallel and terminating with two modules in parallel. The complete unit contained twelve modules, 192 tubes, and had a total nominal membrane surface of 397.44 sq. ft. Membrane Set No. 1 was used in this configuration.

"b" - Five modules in parallel followed by four modules in parallel and terminating with two modules in parallel. The eleven modules, 176 tubes, had a total nominal area of 364.32 sq. ft. The unit ran only a total of 39 hours in three consecutive days using pattern "b". Because of this, no significant data was generated.

"c" - Same sequence as pattern "a". Membrane Set No. 2 was used in this configuration.

"d" - Three modules in parallel, followed by two modules in parallel and terminating with two modules in series. The seven modules, 112 tubes, had a total nominal area of 231.84 sq. ft. Membrane Set No. 2 was used in this configuration.

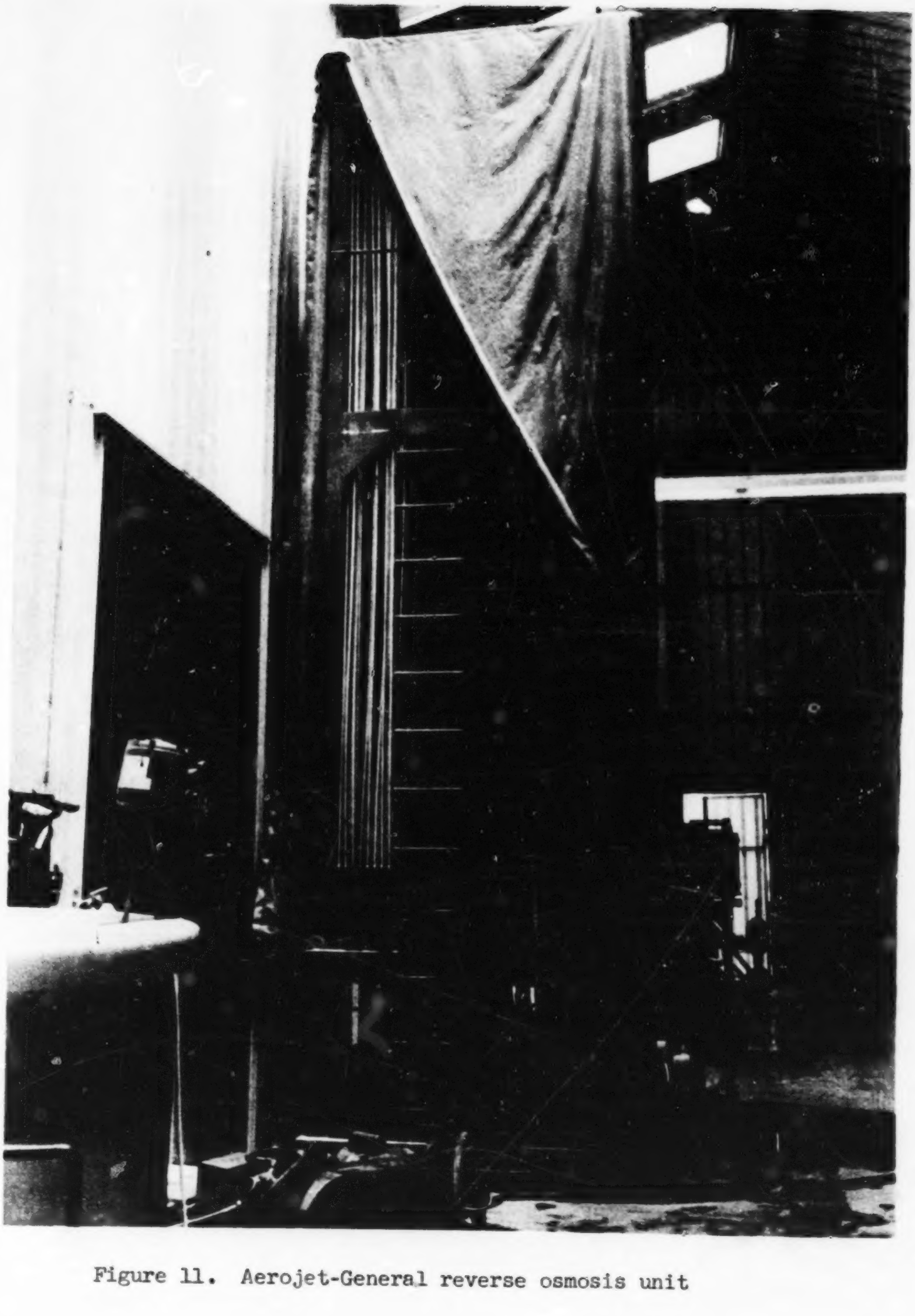


Figure 11. Aerojet-General reverse osmosis unit

Membrane Specifications

A number of different membrane formulations were supplied by Aerojet-General for their unit. Membrane set No. 1 initially contained 160 tubes with membranes formulated from cellulose diacetate using propionamide as the swelling agent. Thirty-two tubes formulated from a "blend" (9-B) of cellulose diacetate and cellulose triacetate and maleic acid swelling agent, were also provided. These tubes were of the cast membrane type with dacron sleeves inserted into fiberglass casings. Membrane set No. 2 was made up initially from whatever tubes were available at the time and included both old and new "high flux" (blend) tubes and "normal-flux" propionamide tubes.

Numerous tube failures occurred during the operating period. Replacements for the failures were made up from whatever tubes were available at the time, resulting in a heterogenous mixture of various membrane formulations at random locations.

Chronological Record

The following notes are taken from the plant data logs to show the major events and changes in operation.

Project Week & Day		
2	4	Start of data collection. Membrane Set No. 1; flow pattern "a". Operated on post treated secondary effluent with the reactor-clarifier, sand and granular activated carbon filters in operation.
3	5	Started recycling part of brine flow to the feed.
4	4	Began in-plant chlorination of reverse osmosis feed.
7	4	Discontinued recycling brine flow to feed.
7	5	Started D.E. filtration of feed.
12	5	Changed to flow pattern "b".
13	3	End of useful data; too many tube failures; no replacements available.
17	7	Unit shut down; no useful data since 13-3.
21	6	Reached an agreement with manufacturer that rental agreement ceased on 15-1.
35	3	Installed replacement tubes at the manufacturer's cost. Membrane Set No. 2; flow pattern "c". Unit restarted on sand and granular activated carbon filtered, pre-unit chlorinated secondary effluent feed.
36	3	Changed to flow pattern "d".
37	6	Large number of tube failures since 35-3; no replacements available; unit permanently removed from service.
43	3	Installation removed by manufacturer.

Data Groupings

The chronological history of the Aerojet-General unit shows that, from

March 9 to November 12, 1970 (weeks 2 through 37) a number of changes in post-treatment conditions, membranes, flow patterns, etc. were made.

Unfortunately the large number of tube failures coupled with the non-availability of suitable replacements made it impossible to collect significant operating information during most of this period. In Table 21 the available data was divided into five major time periods, weeks 2, 3, 4-6, 7-13, and 35-37. While the last time periods had mixed flow patterns they were grouped to make the number of data sets per period as large as possible.

Table 21. REVERSE OSMOSIS PROCESS INFORMATION

AEROJET-GENERAL

Week Nos.	Treatment	Membrane Set	Flow Pattern	Special Conditions
2	A,B,C,E,	1	a	-
3	A,B,C,E	1	a	Brine Recirculation
4-6	A,B,C,E,F,	1	a	Brine Recirculation
7-13	A,B,C,D,E,F	1	a,b	-
35-37	B,C,E,F	2	c,d	-

Mechanical and Operational Problems

The Aerojet-General unit experienced a much greater number of tube or membrane failures than the other R.O. units, although all units operated under essentially identical test conditions. While it is not appropriate to discuss either the design advantages or apparent deficiencies of the reverse osmosis units used in this work, a few factual comments must be made.

1. Aerojet-General initially proposed to furnish a flat-plate unit. In the fall of 1969, they advised that it would be in the study's best interest to substitute a tubular type design because the manufacture of flat plate R.O. units was to be discontinued. Model No. 12-B14-6P-R, one of Aerojet-General's first tubular membranes, was submitted for testing.
2. At the time of the initial installation, the manufacturer provided 38 additional tubes which could be used as replacements, indicating that 20% of a batch of similar tubes had failed when tested in their laboratory. Thirty-eight is exactly 20% of 192, the number of tubes originally installed. Interestingly, however, there was no provision for replacing replacement tubes that failed. At one time Aerojet indicated that an improved type of tube might soon be available. It never was.
3. Twenty tubes had failed by week ten (May 1, 1970). In a letter dated June 11, 1970, (week 15) Aerojet-General was informed that:

> "... A total of thirty leaking membrane tubes (have been removed) since May 1. In each case this required complete shutdown of the unit...
> Usable operational data (were obtained) on only four days since May 15 and on three of these... the operation was at best marginal as (it was necessary) to shut the unit down on three occasions for the replacement of four tubes..."

4. This situation did not improve during subsequent months even after a nearly complete set of replacement tubes had been installed. (From March 9 to November 12, 1970 there were over a hundred tube failures).
5. The long vertical tubes of the Aerojet-General installation were attached, at their ends, to fixed headers by ferrules and usually vibrated while in operation. Most of the observed tube failures occurred at or near the ferrules.
6. Frequently many of the failed tubes could not be replaced without removing adjacent tubes to provide the necessary access.
7. High velocity leaks from a single tube frequently caused adjacent tubes to fail.
8. The area around the unit was very humid due to partial evaporation of the product water, spray from leaking tubes, etc. The canvas enclosure supplied by Aerojet-General (shown in the photograph) was of little value in correcting this condition.
9. Pinhole leaks occurring in the interior of module sets were very difficult to detect. In large numbers, undetected leaks tend to distort data. The data from the 7-13 weekly group is suspected of being distorted because of undetected leaks, as the log A-log time slope for the period is both positive and steep.

From week 2 to week 13 and from week 35 to week 37, there were 2328 available operating hours. The unit actually operated for 2031 hours, or 87.24% of the total time. The major out-of-service hours were as follows:

Table 22. OUT-OF-SERVICE RECORD, AEROJET-GENERAL

	Hours	%
Mechanical problems	-	-
Membrane cleaning	3	.13
Membrane failures	271	11.64
Alterations, additions	9	.39
Feed Treatment Problems	14	.60
Total Down Time	297	12.76

The membrane failure record for the Aerojet-General unit is shown in Table 23. "Failures" have to be shown instead of "replacements" because substitute membranes were rarely available in the necessary quantity.

Table 23. MEMBRANE FAILURE RECORD, AEROJET-GENERAL

Weekly Group	Number of Failures
2	0
3	0
4-6	2
7-12	33
13-35	70 (about)
35-37	26

During weeks 13 to 34, the unit could not be kept in operation long enough to secure any useful operating data. During weeks 35 to 37, the unit was operated on the site under the direct supervision and control of the manufacturer's service personnel. Failures continued to be so numerous that the unit could be run only intermittently and it was finally shut down at their suggestion.

Water Permeability Data

Table 24 shows the permeability data ratios for the Aerojet-General unit. The essential information includes the test parameters (post secondary effluent treatment, membrane set, flow pattern), the average A value, (gm. H_2O/sq. cm - atm - sec), the log A versus log time plot with its standard deviation, the data correlation coefficient and the average gallons per foot per day of product water at about 500 psi .

The various symbols, indices, and ratios used in Table 24 and others which will appear later, are defined and discussed in Sections V, VIII, and the Appendix Section A-1.

The water permeability data show a number of unusual features:

> The average A and the GFD values for weeks 35-37 were both much higher than would normally be expected. It is believed that many leaking tubes went undetected during that period. Well over forty known leaks were isolated and it may be assumed that many others went un-noticed. The log-log slope, its standard deviation and the correlation coefficient, on the other hand, were not abnormal. It is possible that this is an indication that the membranes which were not leaking were becoming fouled at a rapid but relatively constant rate.

Table 24. WATER PERMEABILITY DATA, AEROJET-GENERAL

Week No.	No. Data Sets	Avg. A x 10^5	Log-Log Slope	Std. Dev. Slope	Correl. Coeff.	Avg. G.F.D.	Avg. Effective Op. Pressure (PSI)
2	8	1.235	+0.0117	0.0086	.487	8.91	493
3	4	1.213	-0.0023	0.0123	.132	8.75	497
4-6	15	1.217	+0.0096	0.0099	.259	8.78	501
7-13	25	1.290	+0.0545	0.0152	.600	9.31	547
35-37	9	2.891	-0.0422	0.0178	.668	20.86	508

The data correlation coefficients for weeks 3 and 4-6 are low. During these periods a portion of the final brine flow was recycled to the feed inlet. This was done at the suggestion, and under the direction of the manufacturer's service representative in an attempt to improve the product water recovery ratio which was then close to 0.30. In a letter dated October 1, 1969, (which became part of the rental agreement for this unit) Aerojet-General stated that "sufficient feed pump capacity (would be provided) to support a membrane flux of 20 gal./day sq. ft. of membrane at a 90% recovery factor." At the time this was mistakenly assumed to be an implied estimate of the unit's capability. In any event the actual recovery ratio never coincided with the expected recovery ratio. Additionally, the low correlation coefficients obtained suggest that the recycled brine, because of an inadequate process piping design, was not being uniformly blended with the fresh feed flow before entering the unit.

Water Recovery and Total Rejection Ratios

The product water recovery and the total rejection ratios are shown in Tables 25 through 29. The recovery ratios are the values at the actual operating temperatures. These, rather than the data adjusted to 25°C. (used in the permeability calculations), are required in the determination of the material balance ratios.

Confidence levels for the water recovery ratios were calculated, when possible, for each weekly group:

Table 25. AEROJET-GENERAL WATER RECOVERY DATA

Weekly Period	Membrane Set	Average Recovery Ratio	Standard Deviation	No. Of Data Pts.	80% Confidence Level
2	1	.319	-	1	-
3	1	.306	-	1	-
4-6	1	.368	.118	3	.14 - .69
7-13	1	.424	.116	6	.18 - .67
35-37	2	.556	.044	3	.47 - .64

The wide variability of the data to week 13, as indicated by the broad confidence levels, probably reflects the occurrence of the leaking membranes mentioned previously.

Average Rejection and Material Balance Ratios

The calculated performance factors for the average rejection and material

Table 26. pH ADJUSTED FEED WATER QUALITY, AEROJET-GENERAL

Week Nos.	Constituent Levels (mg/l and micromhos) T.D.S.	Spec. Cond.	Total C.O.D.
2	810.0	1076	28.5
3	710.0	1135	25.3
4-6	786.7	1400	20.5
7-13	743.3	1195	8.5
2-13	758.2	1235	36.7
35-37	800.0	1295	7.1
2-37	764.2	1244	15.6

Table 27. PRODUCT WATER QUALITY, AEROJET-GENERAL

Week Nos.	Constituent Levels (mg/l and micromhos) T.D.S.	Spec. Cond.	Total C.O.D.
2	80.0	367	3.0
3	130.0	173	4.5
4-6	110.0	180	5.7
7-13	190.0	201	1.9
2-13	152.7	208	3.2
35-37	110.0	230	--
2-37	157.9	211	3.3

Table 28. BRINE QUALITY, AEROJET-GENERAL

Week Nos.	Constituent Levels (mg/l and micromhos)			
	T.D.S.	Spec. Cond.	Ca	SO_4
2	-	1477	-	-
3	-	1670	-	-
4-6	1200	1739	-	-
7-12	-	1786	83	436
2-12	-	1718	-	-
35-37	-	2359	-	-
2-37	-	1812	-	-

Table 29. WATER RECOVERY AND TOTAL REJECTION RATIOS, AEROJET-GENERAL

Week Nos.	Water Recovery Ratio	Total Rejection Ratios		
		T.D.S.	Spec. Cond.	Total C.O.D.
2	0.319	0.901	0.659	0.905
3	0.306	0.817	0.848	0.822
4-6	0.368	0.860	0.872	0.722
7-13	0.424	0.744	0.833	0.776
2-13	0.388	0.799	0.832	0.913
35-37	0.556	0.862	0.822	--
2-37	0.424	0.793	0.830	0.789

balance ratios are listed in Table 30. The inter-period variability is minor and this suggests that the various changes in operating conditions had relatively little effect on the membrane's selectivity characteristics. It should be noted that the volume of data was limited. There are two reasons for this: Until July 27, 1970 (week 22) only one chemist was available to make all the laboratory analyses, and numerous shutdowns (resulting from membrane failure) disturbed flow conditions to the extent that it limited the number of representative samples which could be taken.

Table 30. AVERAGE REJECTION AND MATERIAL BALANCE RATIOS, AEROJET-GENERAL

	Avg. Rejection Ratios		Material Balance Agreement Ratios	
WEEK NOS.	T. D. S.	SPEC. COND.	T. D. S.	SPEC. COND.
2	-	.878	-	1.045
3	-	.854	-	1.116
4-6	-	.891	-	1.062
7-13	.900	.850	1.365	.898
2-13	.900	.861	1.365	.968
35-37	-	.875	-	.920
2-37	.900	.864	1.365	.957

Section VIII, (subsection "Reynolds Numbers") lists the Reynolds numbers of four representative operating periods for the Aerojet-General unit. Although the numbers appear to be sufficiently high to retard scale formation on the membrane, the long unsupported tubes vibrated badly as a result of flow turbulance and pressure fluctuation. Higher flow velocities probably would have accentuated this vibration, which was thought to have influenced the incidence of ferrule and membrane failures. It has been reported that Aerojet-General has now abandoned the long tubular design.

Membrane Fouling and Cleansing

This unit was flushed with a cleansing mixture only three times. In each case a 30,000 ppm solution of "Biz" adjusted to pH 8 was used. The first two soakings lasted 15 minutes while the last was completed in 20 minutes. The product flux increased each time, but the first which was most the dramatic (57%) was partially due to increasing the feed pressure from 500 to 610 psi. The flux increases (without changing the feed pressure) for the last two soakings were 19% and 16% respectively. Any relationship that existed between the membrane A value and membrane cleansing is depicted in Figure 13. Flushing data and bench sheets for all units can be found in Appendix A-3.

A Value - Time Plots

Three plots were prepared, using the data shown previously under "Water Permeability", to illustrate the relationship of log A vs. log time for the Aerojet-General unit (Figures 12, 13 and 14). The regression lines in each were determined by modification of Equations (2) and (3) to accomodate the absicssa scale.

Extended comments are unnecessary. The first two plots have positive "b" value slopes while the third shows abnormally high A values. All of these anomalies probably reflect the presence of severe membrane leaks.

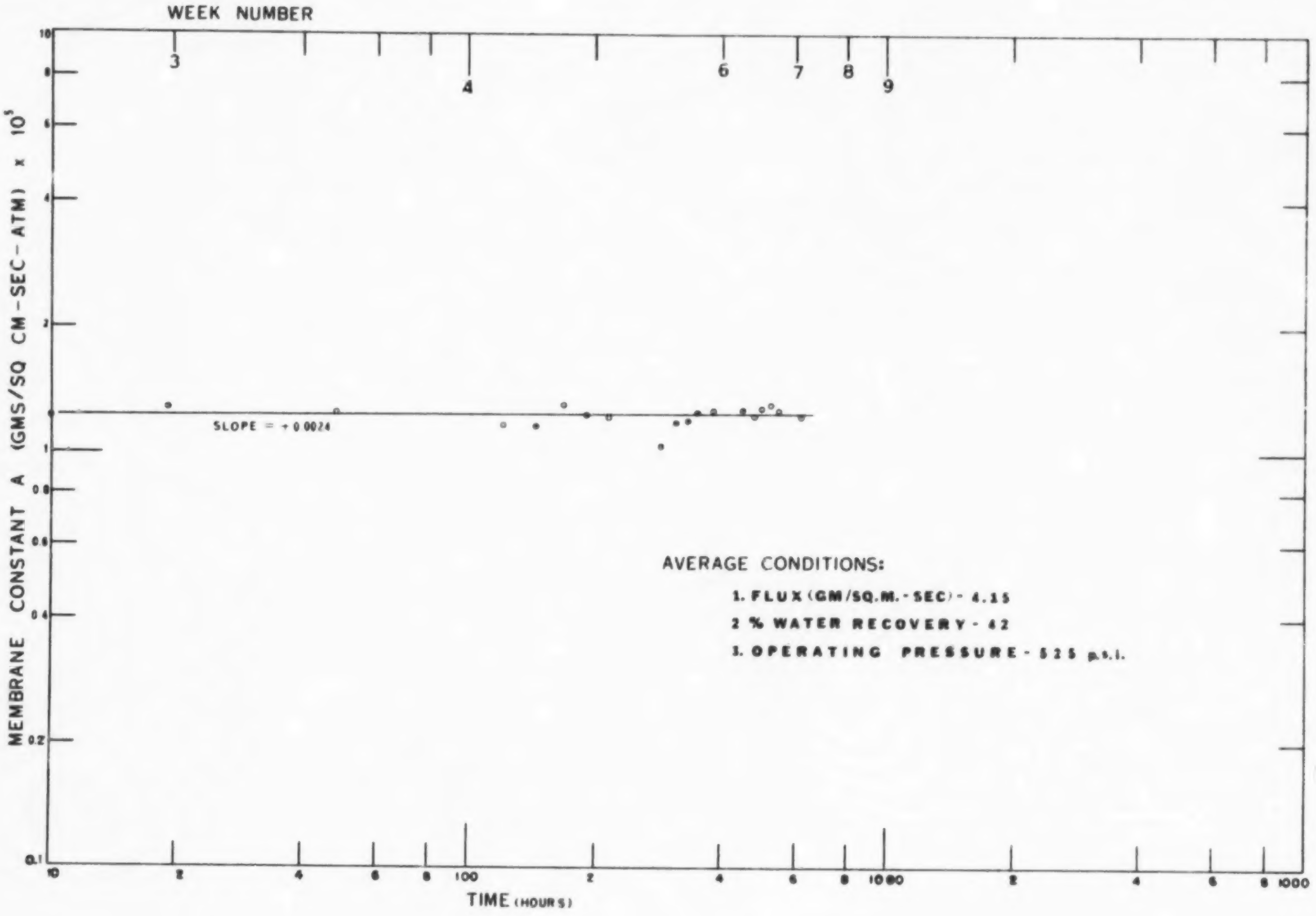


Figure 12. A vs. Time plotted logarithmically, Aerojet-General, 3/18/70 - 4/13/70

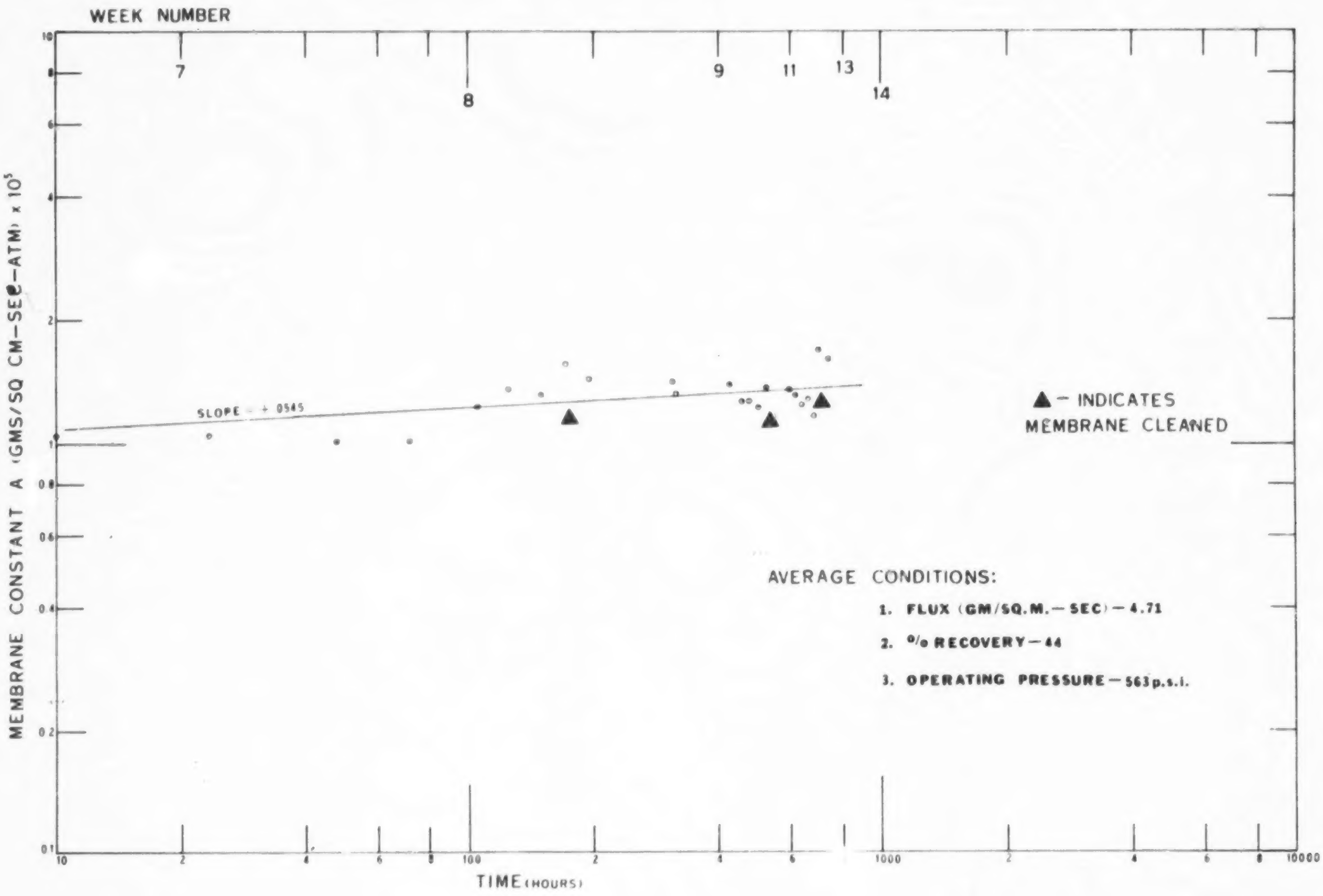


Figure 13. A vs. Time plotted logarithmically, Aerojet-General, 4/14/70 - 5/22/70

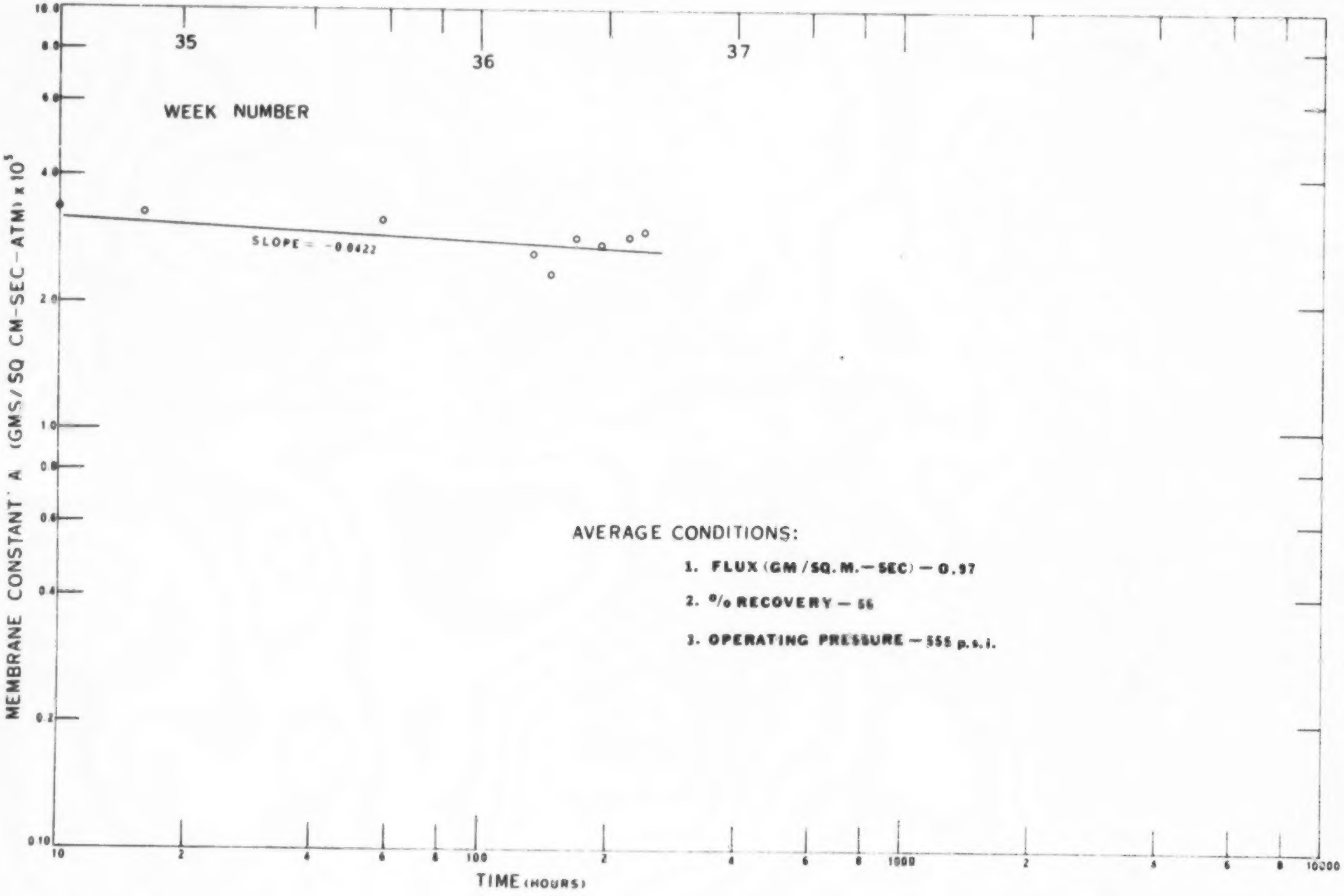


Figure 14. A vs. Time plotted logarithmically, Aerojet-General, 10/27/70 - 11/12/70

SECTION X

AMERICAN STANDARD (ABCOR) REVERSE OSMOSIS UNIT, TUBULAR MEMBRANE DESIGN

Introduction

This unit was leased monthly from the Con Seps Department of American Standard, Incorporated of Hightstown, New Jersey. On December 30, 1970 Abcor acquired the Con Seps Division of American Standard after which the lease agreement was assigned to Abcor. The unit will be discussed as the "American Standard" unit, as it was manufactured by that firm.

The nominal capacity of the Model TM 5-14 unit, as first installed was stated by the manufacturer to be ten thousand gallons per day with a 90% removal of dissolved solids.

The nomenclature and equations used in this section are listed and discussed in Sections V, VIII, and the Appendix.

Physical Configurations

The American Standard unit, (Figure 15) initially contained one hundred vertically-positioned clear plastic tubular shrouds (or modules) each with #316 stainless steel top and bottom end connectors. A module consisted of fourteen five foot long fibre-glass tubes. Each tube contained three components: a cellulosic liner, the osmotic membrane (seamless type) and an indeterminable number (perhaps 130) of spherical ceramic turbulence promoters (Figure 16), each with a diameter of about 0.4 inches. The inside diameter of a tube was approximately 0.5 inches.

The modules had two types of stainless steel end connectors which permitted either parallel or series flow through the tubes composing a module. The flow arrangement was modified on a number of occasions when tube failures occurred and replacements were not obtainable from the manufacturer.

The six major flow patterns are defined below using letter symbols as they will appear in the tables. When the term "parallel" is used, it means the flow through a module is divided equally among the first seven tubes and then after combining the brines, the flow is distributed to the remaining seven tubes in parallel. The term "series" denotes a module as having all fourteen tubes serially connected.

"e" A flow scheme of three parallel rows (each row with thirteen serially-connected "parallel" modules), followed by three parallel rows (each with three serially-connected "parallel" modules), followed by two parallel rows (each with ten serially-connected "parallel" modules), followed by twenty-four serially-connected "parallel" modules, followed finally by four parallel rows (each with two serially-connected "series" modules). Membrane set No. 1 was used, with replacements as available.

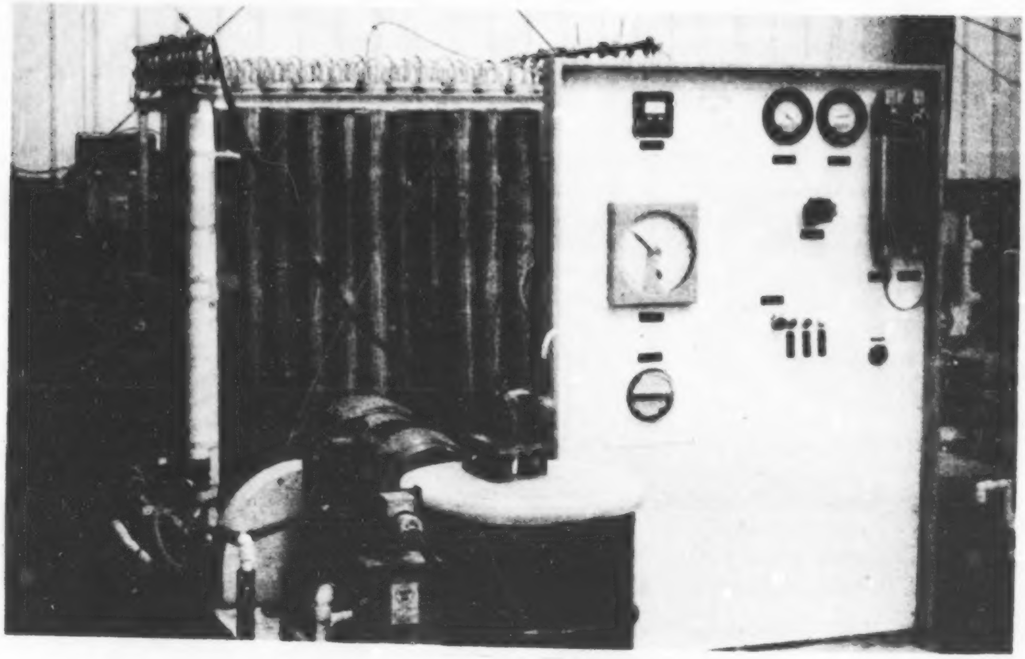
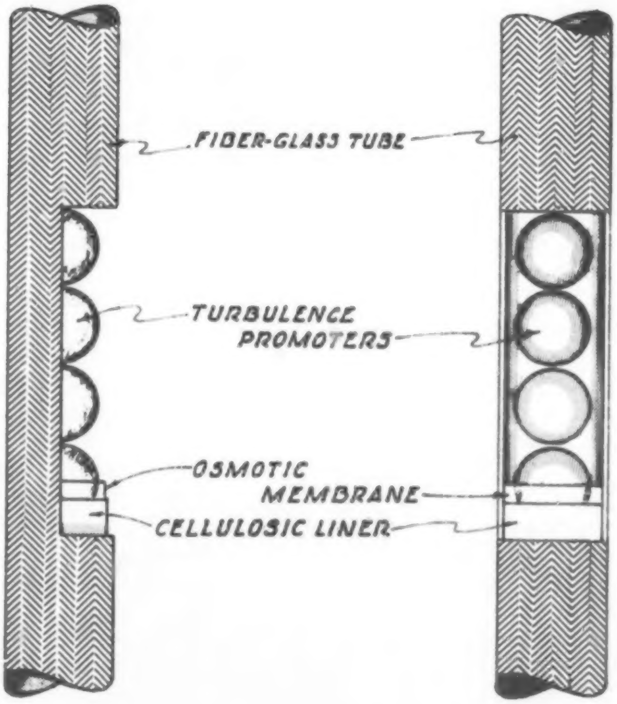


Figure 15. American Standard (Abcor) reverse osmosis unit

Figure 16. Tubular components, American Standard (Abcor) R.O. unit


FIBER-GLASS TUBE
TURBULENCE PROMOTERS
OSMOTIC MEMBRANE
CELLULOSIC LINER

"f"	Same as "e" but with the last eight modules removed. Membrane set No. 1, with replacements, was used in this flow configuration.
"g"	Two parallel rows (each with thirteen series-connected "parallel" modules followed by three parallel rows (each with three series-connected "parallel" modules), followed by two parallel rows (each with ten series-connected "parallel" modules), followed by twenty-four series-connected "parallel" modules, and terminated by four parallel rows, each with two series-connected "parallel" modules. Membrane set No. 1 was used in this configuration.
"h,i"	Heterogeneous flow patterns used in attempts to keep the unit in service when many membrane failures (with few available replacements) required the elimination of modules, or the transfer of modules from one point to another. Membrane set No. 1 was also used in these configurations.
"j"	Three parallel rows (each with thirteen series-connected "parallel" modules) followed by two parallel rows (each with thirteen series-connected "parallel" modules), terminated by fourteen "parallel" modules in series. Membrane set No. 2 was used for this configuration.

No attempt has been made in the above descriptions to assign membrane areas to any of the above nominal flow configurations. Such estimates would have been meaningless because membrane failures often required the shifting of modules from one place to another or even the complete elimination of various sections within the basic pattern. Accurate records were kept, however, of the total membrane surface area in use on any given day and these data formed the basis of the water permeability information shown in Table 34.

With the lack of consistent membrane areas and because the turbulence promotors introduced unknown variables, Reynolds Numbers were not estimated for the American Standard unit.

Membrane Specifications

The manufacturer stated that "...The original American Standard membranes were subjected to a standard test with 5000 ppm NaCl solution at 600 psi and 77°F...Flux rates ranged from 9 to 13 gpd/sq. ft. with an average of around 10.5 gpd/sq. ft. Rejection was found to range from 89 to 95% NaCl rejection with an average of 91%..." These membranes were termed AS-90+(90% rejection) membranes. Some AS-197 membranes were installed early in October, 1970.

The second set of modules, installed by Abcor in early April, 1971, were "similar" to the first except that the membranes were narrow "Eastman No. KP-96" cellulose acetate sheets rolled into a tubular shape with the longitudinal edges sealed. They were protected from the resin impregnated fiberglass tubes by thin strips of Du Pont "Re-May" paper. (American Standard had reportedly used "some"

Eastman membranes of "... a different type and a better quality..." in the earlier installation.)

Chronological Record

The following notes have been extracted from the plant data log sheets to show the major events and changes in operation during the study:

Week	Day	
6	5	Portion of equipment received in Hemet. Balance delayed by labor problems not associated with either Eastern Municipal Water District or American Standard.
11	3	Balance of major equipment received.
14	5	Start of data collection. Membrane Set No. 1; flow pattern "e". Started unit with reactor-clarifier, sand granular activated carbon, and D.E. filters in operation with pre-R.O. unit chlorination and pH adjustment of feed.
18	6	Removed about 8% of the modules because of membrane failures; flow pattern "f". Membranes in last section became coated with tri-calcium ortho-phosphate scale sometime between weeks 18 and 23.
28	1	Discontinued D.E. filtration of feed.
31	7	More membrane failures. Changed to flow pattern "g".
34	1	Discontinued reactor-clarification.
35	7	Changed to flow pattern "h".
36	5	Changed to flow pattern "i".
38	1	Out of service - feed pump bearing failures.
to		
38	6	
41	4	Resumed reactor-clarification of feed.
47	1	Many more membrane failures; no replacements available. Removed unit from service.
56	3	Equipment lease agreement terminated by mutual consent.
61	3	Replacement membranes received. Set No. 2 installed; flow pattern "j". Operated using sand filtration with pre-R.O. unit chlorination, (also pH adjustment).
64	4	Discontinued sand filtration of feed. Operated on pre-R.O. unit chlorinated, pH adjusted, secondary effluent.
69	7	Stopped testing program.

Data Groupings

The R.O. units used in this study were subjected to relatively stable conditions between process changes. These process changes were mainly limited to modification of flow patterns, module replacements and variation in the degree of feed treatment. In the case of the American Standard Unit, the conditions were often difficult to define. The unit had numerous membrane failures and since replacements were often unavailable, the flow pattern within the unit was seldom consistent for any reasonable length of time.

As individual modules were gradually removed from service or to other locations, it became necessary in some instances to by-pass a group of modules. When replacements were available, they were inserted within groups of older sets. Under these conditions, it should be evident that a portion of the tubular data, computed or observed, may be invalid.

The data time groupings for the American Standard unit were rather arbitrarily separated into the weekly sets shown in Table 32.

Mechanical and Operational Problems

The operation of the American Standard unit presented problems in four major areas: the feed pump, the design features of the installation, the membrane failure rate and the availability of replacement modules.

The feed pump was initially a duplex FWI (Frank Wheatley Industries, Tulsa, Oklahoma) plunger pump. Within two weeks, it was replaced by a FWI, P-220A, triplex plunger pump to eliminate backlash in the gears of the U.S. Motors Vari-Drive. The second pump was shut down many times for short periods to correct packing and bearing problems and once, for about a week, to make a complete over-haul.

The basic design of the American Standard unit made it difficult to replace or isolate leaking modules and to remove foreign material (mostly turbulence promotors) in the product water lines and fittings.

Both American Standard and Abcor were frequently delinquent in providing replacement modules as required, and this accounted for the unit being out of service for one hundred days (weeks 47 to 61) of the study. Consequently, it was impossible to test the unit on reactor-clarified sand filtered secondary effluent without carbon filtration.

During July and early August, 1970 (weeks 19 to 22) membrane deposits of a scale, chemically identified as tri-calcium ortho phosphate, were found in the last section of the unit. It is believed that the scale deposits formed as a result of operating at nearly a 90% product water recovery. When the product water recovery was lowered to approximately 80% and after cleansing the membrane with a 3.5 pH sulfuric acid/water solution, the unit appeared to be free of the deposition problem. There were 6868 available operating hours in weeks 14 to 46 and 61 to 69. The unit was on the line for 94.42% of this time (6485 hours). The major out-of-service periods were as follows:

Table 31. OUT-OF-SERVICE RECORD, AMERICAN STANDARD

	Hours	%
Mechanical Problems	158	2.30
Membrane Cleaning	32	.46
Membrane Failures	162	2.36
Alterations, Additions	11	.17
Post-Treatment Problems	20	.29
Total Down Time	383	5.58

Table 32. REVERSE OSMOSIS PROCESS INFORMATION, AMERICAN STANDARD

Week Nos.	Secondary Post-Treatment	Membrane Set	Flow Pattern
14-18	A,B,C,D,E,F	1	e
19-22	A,B,C,D,E,F	1	f
19-28	A,B,C,D,E,F	1	f
24-28	A,B,C,D,E,F	1	f
29-31	A,B,C,E,F	1	f
32-33	A,B,C,E,F	1	g
34-35	B,C,E,F	1	g
36	B,C,E,F	1	h
37	B,C,E,F	1	i
38-40	B,C,E,F	1	i
41-46	A,B,C,E,F	1	i
14-46	VARIOUS	1	VARIOUS
61-63	B,E,F	2	j
64-69	E,F	2	j
61-69	VARIOUS	2	j

Post-Treatment Legend

A = Reactor-Clarifier
B = Sand Filters
C = Carbon Filters
D = D.E. Filters
E = Pre-R.O. Unit Chlorination
F = pH Control

Table 33 shows the membrane failures according to time grouping:

Table 33. MEMBRANE FAILURE TABULATION, AMERICAN STANDARD

Weekly Group	Number of Failures
14-18	5
19-28	13 (scaling problems)
29-31	5
32-33	14
34-35	0
36	6
37	7
38-40	11
41-46	7
61-63	11
64-69	10
	Total 89

Water Permeability Data

Inspection of data from Table 34 reveals the log A vs log time slope for weeks 19 to 28 to be quite different from that for weeks 19 to 22 and 24 to 28. There are two possible reasons for this difference. First, the A value for weeks 19 to 22 was low because of calcium phosphate build-up on the membrane. Second, the average A value for weeks 24 to 28 was unusually high because of one high daily value, (2.874) possibly caused by an undetected leak in the membrane.

For weeks 41-46 the data correlation is very low. Log A versus log time slope is nearly horizontal (tan =-0.0004). There were a couple of causes for these abnormalities of horizontal slope. An EDTA flush about midway through the period was partially responsible for maintaining high A values. Additionally, numerous unscheduled shut-downs relaxed the membranes. Although never considered as a standard cleaning procedure, membrane relaxation is thought to be helpful in maintaining cleaner membranes; through relaxation higher permeation rates and A values could have resulted. Conceivably, the high A values and fluxes encountered after week 61 can be correlated to the new membrane set put into service at week 61 and/or to undetected leaks which occurred after week 61. "New" membranes usually show better fluxes and rejection ratios than "old" ones. Indeed, the flux did increase, but the product quality and rejection ratios remained about the same as in previous periods. This suggests the possibility that undetected leaks contributed to the high fluxes especially if the number of membrane failures is proportional to the number of undetected leaks. From Table 33, it can be seen that membrane failures occurred at a rather constant rate throughout the American Standard study; assuming the latter proportion exists, the quality of product would be maintained

Table 34. WATER PERMEABILITY DATA, AMERICAN STANDARD

Week Nos.	No. Data Sets	Avg. A $\times 10^5$	Log-Log Slope	Std. Dev. Slope	Correl. Coeff.	Avg. G.F.D.	Avg. Effective Op. Pressure (P.S.I.)
14-18	17	1.796	-0.1389	0.0310	.757	12.96	409
19-22	21	1.394	-0.0244	0.0135	.382	10.06	491
19-28	47	1.547	+0.0232	0.0156	.216	11.16	455
24-28	25	1.621	-0.0259	0.0043	.779	11.70	444
29-31	14	1.533	-0.0094	0.0038	.582	11.06	538
32-33	10	1.559	-0.0024	0.0049	.167	11.25	499
34-35	9	1.477	-0.0087	0.0050	.549	10.66	505
36	3	1.559	-0.0116	0.0018	.989	11.25	508
37	7	1.464	-0.0130	0.0038	.839	10.56	513
38-40	11	1.459	-0.0099	0.0048	.565	10.53	498
41-46	27	1.440	-0.0004	0.0041	.022	10.39	505
14-46	147	1.540	-0.0627	0.0084	.527	11.11	479
61-63	14	2.092	-0.1034	0.0119	.928	15.09	523
64-69	26	1.807	-0.0669	0.0143	.668	13.04	400
61-69	40	1.907	-0.0920	0.0129	.756	13.76	429

partially as a function of undetected membrane leaks. Thus, it is reasonable to suspect both the "new" membrane and membrane leaks as contributing to high fluxes after week 61.

Water Recovery and Total Rejection Ratios

Feed,product and brine water quality plus product water recovery and total rejection ratios for the American Standard unit are shown in Tables 36 through 39 . Confidence levels for the recovery ratios can be found in Table 35. The recovery ratios seem relatively consistent until week 64, three weeks after the second membrane set was installed, but almost simultaneous with the application of untreated secondary effluent.

Because of the reasonable interval between weeks 61 and 64, the formulation character of Membrane Set No. 2 was assumed to play a minor role in reducing the recovery ratios after week 64. Alternatively, the deteriorated feed quality of secondary effluent could and presumably did magnify the effects of fouling, giving lower recovery ratios and higher rejection ratios. The slime growth as mentioned in Section VIII ("Membrane Fouling and Cleansing") and particulate fouling was probably the major reason for the rapid change in recovery ratios after week 64.

Table 35. WATER RECOVERY DATA CONFIDENCE LEVELS

Weekly Period	Average Recovery Ratio	Standard Deviation	No. Of Data Pts.	Range @ 80% Confidence Level
14-18	.889	.033	5	.84 - .94
19-28	.805	.051	10	.73 - .88
14-28	.833	.061	15	.75 - .92
29-31	.739	.020	3	.70 - .78
19-31	.790	.054	13	.72 - .86
32-33	.765	.016	2	.72 - .81
29-33	.749	.014	5	.73 - .77
34-35	.754	.026	2	.67 - .83
38-40	.756	.025	3	.71 - .80
34-40	.774	.052	7	.70 - .85
41-46	.689	.023	6	.66 - .72
14-46	.782	.072	33	.69 - .88
61-63	.724	.010	3	.70 - .74
64-69	.527	.040	6	.47 - .59
61-69	.593	.104	9	.45 - .74
14-69	.741	.111	42	.60 - .89

Table 36. pH ADJUSTED FEED WATER QUALITY, AMERICAN STANDARD

			CONSTITUENT LEVELS (mg/l and micromhos)							
WEEK NOS.	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARDNESS	ORTHO-P	TOTAL ALKAL.	NO_3-N	SULFATE
14-18	765.0	1205.4	110.09	3.42	7.80	133.49	-	55.91	3.90	387.26
19-28	745.5	1413.4	130.25	7.57	5.47	201.51	4.79	54.37	4.18	341.17
14-28	753.2	1370.4	127.77	7.85	6.06	189.26	4.79	54.87	4.14	348.93
29-31	740.0	1201.3	120.10	5.94	4.48	201.23	7.91	-	4.90	373.29
19-31	746.5	1364.2	129.09	7.19	5.23	200.37	5.55	54.37	4.28	350.30
32-33	715.0	1264.7	-	5.85	4.48	214.23	6.71	42.26	1.30	346.15
29-33	730.0	1228.3	82.77	5.89	4.43	205.92	7.50	42.26	3.10	359.85
34-35	775.0	1271.3	-	10.25	6.33	213.97	10.42	25.92	-	398.50
36	800.0	1266.5	-	-	-	235.42	-	-	-	-
37	730.0	1384.6	-	8.70	5.20	222.22	14.95	33.49	-	363.63
38-40	795.0	1269.4	130.99	14.62	6.56	223.33	14.04	67.91	-	383.18
34-40	778.3	1263.0	130.99	11.44	5.72	222.82	13.49	44.28	-	385.71
41-46	772.0	1233.5	126.44	7.93	3.61	233.49	7.46	30.67	-	370.23
14-46	757.5	1305.2	127.40	8.35	5.48	207.76	7.43	43.15	3.91	365.08
61-63	853.3	1313.0	155.80	4.69	-	229.62	12.08	18.90	-	444.67
64-69	810.8	2048.6	138.39	56.78	32.08	232.38	12.00	54.44	3.81	379.09
61-69	825.0	1798.7	171.87	53.53	32.08	238.18	12.22	41.17	3.81	416.67
14-69	773.1	1416.1	133.24	18.15	9.89	215.41	8.65	42.53	3.87	378.18

Table 37. PRODUCT WATER QUALITY, AMERICAN STANDARD

			CONSTITUENT LEVELS (mg/l and micromhos)							
WEEK NOS.	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARDNESS	ORTHO-P	TOTAL ALKAL.	NO_3-N	SULFATE
14-18	241.5	527.0	24.0	3.64	3.20	57.00	-	20.80	2.20	146.00
19-28	161.0	367.5	56.14	2.34	1.33	25.39	.91	18.65	3.18	29.00
14-28	184.0	420.7	52.13	2.77	1.80	30.66	.91	19.37	3.04	45.71
29-31	160.0	276.3	49.00	1.30	0.47	32.60	1.10	-	2.90	54.50
19-31	160.8	346.5	55.25	2.10	1.11	27.05	.96	18.65	3.14	35.38
32-33	175.0	322.5	-	2.10	1.65	29.35	.96	19.10	1.20	40.50
29-33	166.0	294.8	49.00	1.62	0.94	31.30	1.05	19.10	2.05	47.50
34-35	190.0	314.0	-	1.65	0.95	29.10	2.00	11.95	-	53.00
36	150.0	461.0	-	-	-	22.60	-	-	-	-
37	110.0	270.0	-	4.10	1.40	22.00	1.60	14.20	-	28.00
38-40	150.0	298.3	41.00	4.65	2.40	26.80	1.60	14.60	-	41.00
34-40	156.7	322.0	41.00	3.34	1.62	26.07	1.70	13.46	-	43.20
41-46	140.0	265.2	44.00	0.92	0.65	30.12	0.85	12.30	-	48.50
14-46	168.2	352.4	48.92	2.37	1.49	29.71	1.05	15.36	2.82	46.00
61-63	86.7	131.3	26.33	1.50	-	5.97	0.29	13.53	-	6.67
64-69	56.7	147.5	15.50	3.35	3.08	4.88	0.18	12.25	1.64	4.17
61-69	66.7	142.1	22.00	2.73	3.08	5.24	0.22	12.68	1.64	5.00
14-69	144.8	307.3	41.44	2.45	1.76	23.91	0.83	14.46	2.35	33.28

Table 38. BRINE QUALITY, AMERICAN STANDARD UNIT

WEEK NOS.	T.D.S.	SPEC. COND.	mg/l except spec. cond. as micromhos CHLORIDE	TOTAL C.O.D.	TOTAL HARD-NESS	ORTHO-P	ALKA-LINITY	CALCIUM	NO_3-N
14-18	-	9731	-	-	-	-	-	-	
19-28	-	7967	-	69.0	-	-	-	-	6.5
14-28	-	8756	-	69.0	-	-	-	-	6.5
29-31	3072	4659	464	25.3	847	32.2	49.0	224	2.7
19-31	2996	6375	500	31.4	812	71.5	-	222	4.2
32-33	2399	4266	-	10.9	540	24.7	29.0	197	1.7
29-33	2798	4494	464	19.6	694	34.0	42.0	215	2.4
34-35	2960	3935	-	35.5	795	52.0	6.8	-	0.1
36	-	5367	-	-	-	-	-	-	-
37	2818	4395	-	30.0	857	57.5	306	-	-
38-40	2625	3726	387	25.7	934	51.3	156	-	2.8
34-40	2732	4097	387	29.7	875	53.5	125	-	2.[illegible]
41-46	2204	2970	266	21.1	671	26.3	740	-	14
14-46	2633	5528	436	27.2	747	52.4	98.0	217	-
61-63	2678	3690	357	100	774	46.3	39.0	-	-
64-69	1706	2694	284	87.2	514	25.4	44.1	210	6.4
61-69	2070	3042	339	90.9	611	33.3	41.5	210	6.4
14-69	3245	4938	-	88.3	522	23.0	82.0	210	4.7

Table 39. WATER RECOVERY AND TOTAL REJECTION RATIOS, AMERICAN STANDARD

WEEK NOS.	WATER RECOVERY RATIO	TOTAL REJECTION RATIOS T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARDNESS	ORTHO-P	TOTAL ALKAL.	NO_3-N	SULFATE
14-18	.889	.684	.590	.782	.568	.590	.573	-	.628	.436	.623
19-28	.805	.785	.740	.569	.691	.757	.874	.810	.657	.239	.915
14-28	.833	.755	.693	.592	.647	.703	.838	.810	.647	.266	.869
29-31	.739	.784	.770	.592	.781	.895	.838	.861	-	.408	.854
19-31	.790	.785	.746	.572	.708	.786	.865	.827	.657	.267	.899
32-33	.765	.755	.745	-	.641	.629	.863	.857	.548	.077	.883
29-33	.749	.773	.760	.592	.725	.788	.848	.860	.548	.339	.868
34-35	.754	.755	.753	-	.839	.850	.864	.818	.539	-	.867
36	.825	.812	.636	-	-	-	.904	-	-	-	-
37	.819	.849	.805	-	.529	.731	.901	.893	.576	-	.923
38-40	.756	.811	.765	.687	.682	.634	.880	.886	.785	-	.893
34-40	.774	.799	.750	.687	.708	.717	.883	.874	.696	-	.888
41-46	.689	.818	.785	.652	.884	.820	.871	.886	.599	-	.869
14-46	.782	.778	.730	.616	.716	.728	.857	.857	.644	.278	.874
61-63	.724	.898	.900	.831	.968	-	.974	.976	.284	-	.985
64-69	.527	.930	.928	.888	.941	.904	.979	.985	.775	.570	.989
61-69	.593	.919	.921	.852	.949	.904	.978	.982	.692	.570	.988
14-69	.741	.813	.783	.689	.865	.822	.889	.904	.660	.393	.912

Accompanying these lower recovery ratios and higher rejection ratios was the side benefit of greater brine flow rates which in turn gave Reynolds numbers sufficient to maintain the membrane surface relatively free of deposited material.

Average Rejection and Material Balance Ratios

The average rejection and material balance ratios are shown in Table 41. The values were calculated from Equations (7) and (14). The average rejection ratios are higher after week 61. The material balance ratios are normally within an acceptable plus or minus 10% except for total C.O.D. It is evident that some of the latter analyses are in error.

Membrane Fouling and Cleaning Procedures

American Standard membranes were flushed twenty-two times with a Biz solution, three times with a weak sulfuric acid water solution and twice with EDTA solution. Some pertinent information relative to membrane cleaning is given in Table 40, while summaries of the bench sheets of membrane cleansing procedures can be found in Appendix A-3.

Table 40. MEMBRANE CLEANSING HISTORY AND PRODUCT FLUX INCREASES (%)

AMERICAN STANDARD

Weekly Group	Biz		Acid Wash		EDTA	
	No. Times	(%)	No. Times	(%)	No. Times	(%)
14-18	1	-	-	-	-	-
19-22	3	8.7	-	-	-	-
24-28	2	4.6	-	-	1	22.2
23-31	1	5.5	-	-	-	-
34-35	1	3.0	-	-	-	-
38-40	1	-	-	-	-	-
41-46	1	-	-	-	1	-
61-63	4	5.6	3	3.9	-	-
64-69	8	23.3	-	-	-	-
Total No. and Per Cent	22	11.7	3	3.9	2	22.2

A Value - Time Plots

Two plots prepared (Figures 17 and 18) using the original plant data are summarized in Table 34.

Figure 17, for weekly groups 14 to 46, shows the effect of the phosphate scale formation discussed previously and the A value recovery after corrective measures were taken. Figure 18, shows data for weeks 61 to 69, during which the unit feed was untreated secondary effluent except for pre-R.O. unit chlorination and pH adjustment.

Table 41. AVERAGE REJECTION AND MATERIAL BALANCE RATIOS, AMERICAN STANDARD UNIT

Week Nos.	Average Rejection Ratios						Material Balance Agreement Ratios					
	T.D.S.	Spec. Cond.	Total C.O.D.	Total Hard-Ness	Ortho-P	NO_3-N	T.D.S.	Spec. Cond.	Total C.O.D.	Total Hard-Ness	Ortho-P	NO_3-N
14-18	-	.900	-	-	-	-	-	1.148	-	-	-	-
19-28	.925	.903	.890	.959	.936	.405	1.079	1.051	1.325	1.050	1.267	1.038
14-28	.925	.902	.890	.959	.936	.405	1.079	1.083	1.325	1.050	1.267	1.038
29-31	.915	.892	.918	.931	.942	.567	1.222	1.016	1.294	1.328	1.084	.888
19-31	.920	.900	.897	.945	.938	.459	1.151	1.043	1.317	1.189	1.198	.988
32-33	.882	.871	.815	.942	.941	.368	.924	.885	.884	.973	.938	1.147
29-33	.902	.883	.877	.936	.942	.468	1.103	.963	1.113	1.151	1.026	1.017
34-35	.894	.875	.928	.942	.936	-	1.081	.910	1.085	1.008	1.383	-
36	.926	.846	-	-	-	-	.870	.951	-	-	-	-
37	.935	.901	.790	.959	.958	-	.785	.696	1.017	.781	.837	-
							-	-	-	-	-	-
38-40	.918	.888	.776	.951	.954	-	1.081	.925	.774	1.101	1.095	-
34-40	.914	.880	.840	.949	.950	-	.997	.892	.947	1.000	1.102	-
41-46	.904	.877	.935	.935	.942	-	.989	.930	.961	1.011	1.106	-
14-46	.910	.890	.886	.942	.942	.436	1.036	.997	1.130	1.045	1.125	1.028
61-63	.952	.948	.975	.988	.990	-	.972	.816	.547	.950	1.040	-
64-69	.955	.951	.953	.987	.991	.662	1.032	.958	.776	1.034	1.050	1.134
61-69	.954	.950	.959	.987	.990	.662	1.012	.910	.719	1.006	1.046	1.134
14-69	.924	.903	.904	.958	.957	.572	1.028	.978	1.027	1.032	1.101	1.092

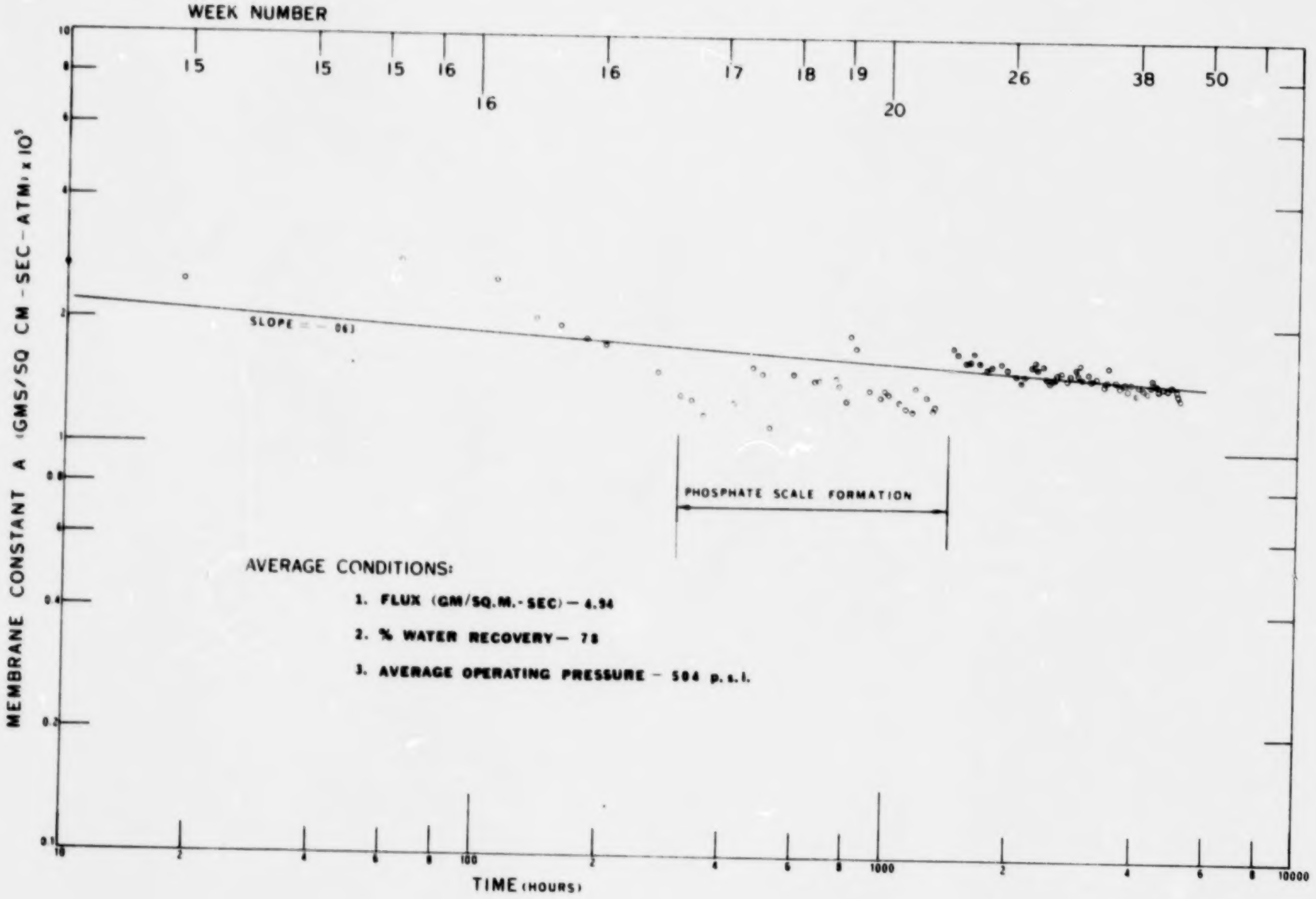


Figure 17. A vs. Time plotted logarithmically, American Standard, 4/26/71 - 6/25/71

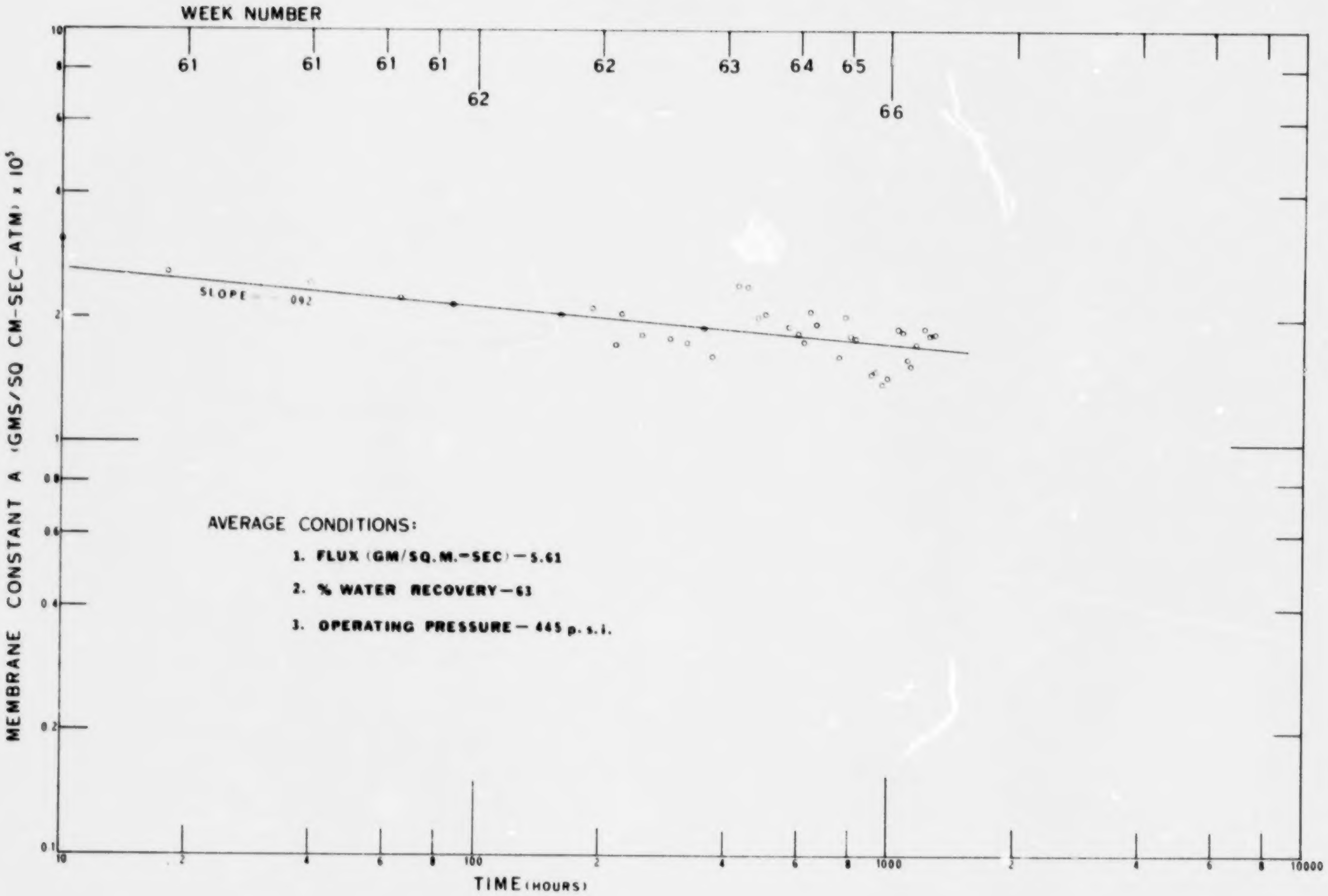


Figure 18. A vs. Time plotted logarithmically, American Standard, 6/3/70 - 1/15/71

SECTION XI

E. I. DU PONT DE NEMOURS & CO. UNIT

HOLLOW FIBER CONCEPT

Introduction

One unit used in this study was the Du Pont "Permasep"® Pilot Plant furnished complete with permeators, pump and instrumentation. The unit capacity was rated at 10,000 gal./day with a 75 to 90% product water recovery at 600 psi. Figure 19 shows the unit as installed.

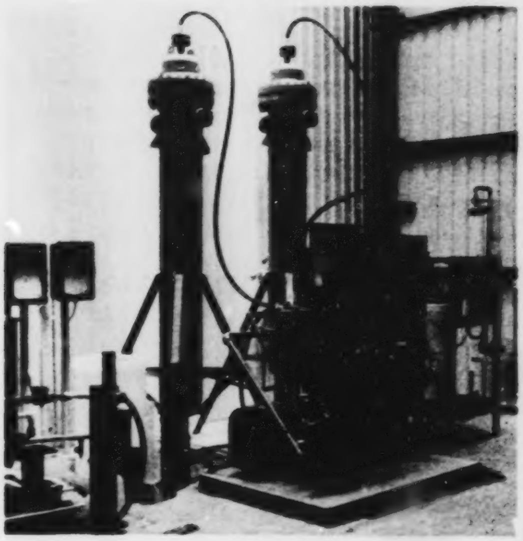


Figure 19. Du Pont unit with B-5 permeators in place

Physical Configuration of Modules

Two different "Permasep" modules were tested. The first, called a B-5 type, was a 15 in. O.D. by 10.5 ft. dished and flanged cylinder enclosing a draped set of hollow nylon fibers (see next sub-section for their description). The nylon fibers were suspended from an epoxy tube sheet and confined by a nylon net wrapping. Within the bundle was a vertical, centrally-positioned feed tube having numerous 100 micron (0.01 cm) flow distribution holes.

Midway through the testing period the two B-5 permeators were replaced by five smaller modules. These modules, called the B-9 type, were small 6063-T6 horizontal aluminum cylinders, about 5.5 in. O.D. by 47 in. long.

Each permeator type used the same basic test unit package, consisting of the equipment shown in Figure 20 and described in Table 42.

In both cases, the feed enters the permeator casing or shell and contacts the bundle of hollow membrane fibers. A portion of the water permeates the fibers;the rest is rejected as brine.

Figures 21 and 22 show the general flow patterns through each of the module types.

The two B-5 modules were operated in series, with the brine from the first being used as the feed for the second. The product flows were combined to give an average flow and product quality. This configuration was designated as flow pattern "k".

Two module configurations were tested using B-9 modules. The first, designated as the "t" pattern, consisted of three modules in parallel followed by two in parallel. The "u" pattern consisted of five modules in parallel and was adopted (at Du Pont's suggestion) with the expectation that the product recovery might be improved, since each permeator would receive the same high inlet pressure. The results, which will be discussed in subsequent sub-sections, were not encouraging. In order to equalize the input flow to all five modules, flow constrictors (balancing "venturies") were placed at each brine port.

The venturies were stainless steel tubes, about 3.75 cm long by 0.1 cm I.D. which occasionally became partially clogged. This condition was accompanied by a substantial reduction in brine flow. If undetected and uncorrected, the problem rapidly became worse, which introduced still other problems.

With a restricted flow, the introduction of cleansing solutions was a slow and difficult process. It was also necessary to estimate brine pressure within the modules by calculation, rather than by average. Such estimates, however, could not be confirmed readily. It was eventually realized that the fouling tendency, as a function of lower flow rates per module, was much greater in the "u" pattern (5 in parallel) than in the "t" pattern.

Membrane Specifications

The B-5 modules contained hollow, semi-porous formic acid-treated nylon (perhaps the 6.6 type) non-asymmetric fibers with the Du Pont name "ZYTEL". The fibers were approximately 25 microns I.D. and 50 microns O.D. with total membrane surface area for the two permeator modules estimated by the manufacturer at 160,900 sq. ft.

The B-9 modules contained hollow formic acid treated asymetric aromatic polyamide fibers (Du Pont "NOMEX") having the dimensions of 40 microns I.D. and 80 microns O.D. The actual surface area of the B-9 modules varied as shells (modules) were replaced (see sub-section "Chronological Record"). The manufacturer's estimated areas for the four modifications are listed in Table 43.

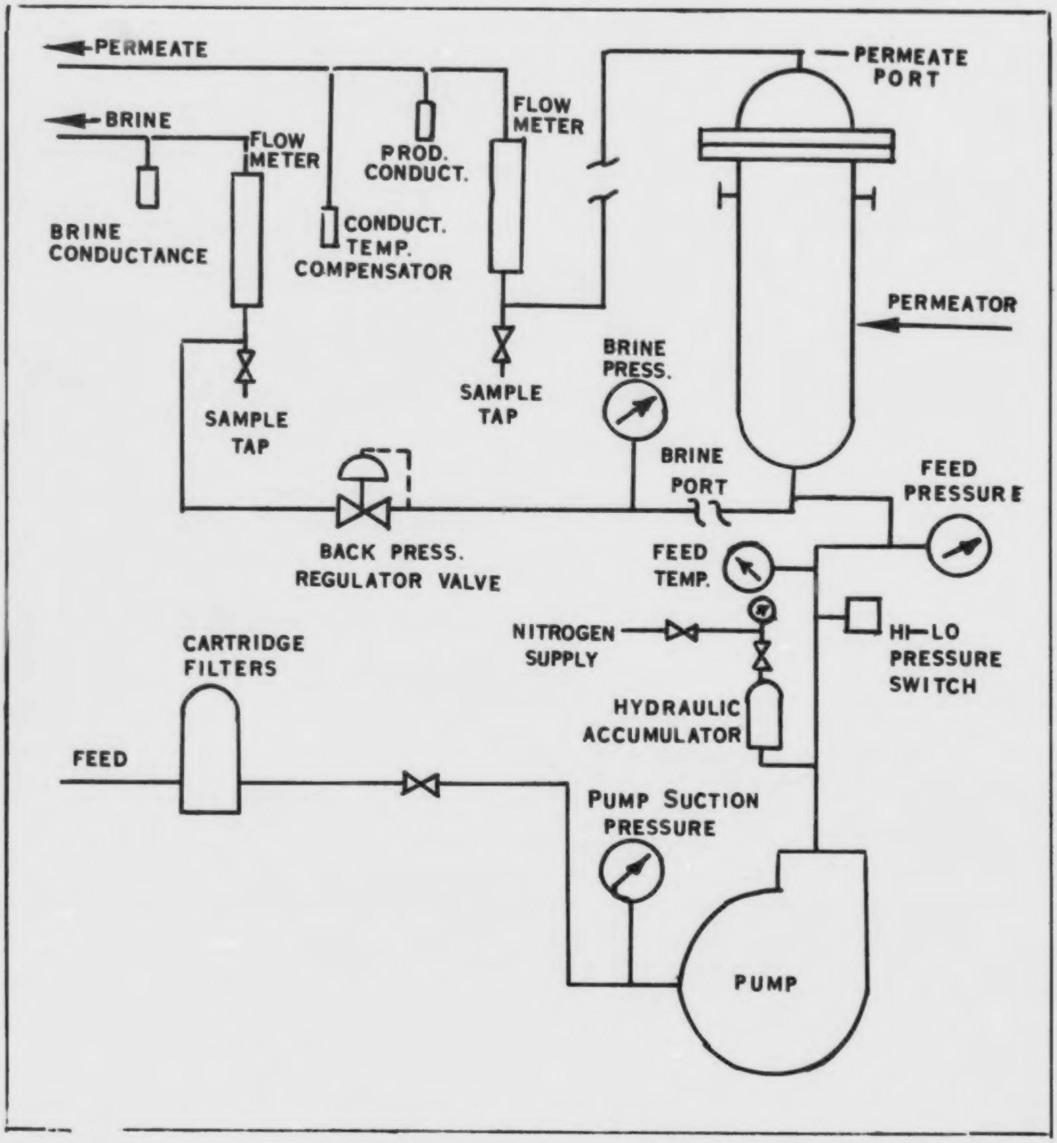

PERMEATE
BRINE
FLOW METER
PROD. CONDUCT.
FLOW METER
PERMEATE PORT
BRINE CONDUCTANCE
CONDUCT. TEMP. COMPENSATOR
PERMEATOR
BRINE PRESS.
SAMPLE TAP
SAMPLE TAP
BRINE PORT
FEED PRESSURE
BACK PRESS. REGULATOR VALVE
FEED TEMP.
NITROGEN SUPPLY
HI—LO PRESSURE SWITCH
CARTRIDGE FILTERS
HYDRAULIC ACCUMULATOR
FEED
PUMP SUCTION PRESSURE
PUMP

Figure 20. 14" Permasep® pilot plant flow diagram (Courtesy, Du Pont)

Table 42. EQUIPMENT DESCRIPTION, DU PONT PERMASEP® PACKAGE

Item	Description
Pump	Positive displacement, reciprocating, triplex, Armco Model J-231-L.
Hydraulic Accumulator	Greer 3,000 psi bladder accumulators for water service. Model 30A-IWS.
Flow Meter	Fisher and Porter Model No. 10A2735A.
Pressure Gauge	Ashcroft Maxisafe Gauge Type 1020P, 0-100 psig range.
Pressure Gauge	Ashcroft Maxisafe Gauge Type 1377TAS, 0-1500 psig.
Filter	Cuno Micro Klean Fiber Cartridge Filter 316, Model 3AxB1 with 5 micron wool cartridges.
Temperature Gauge	Ashcroft Dial Thermometer Cat. No. 2-6360BH, 0-100° C.
Back Pressure Regulator	Maratta Back Pressure Regulator Model TRV 533-1A, Part No. 806325.

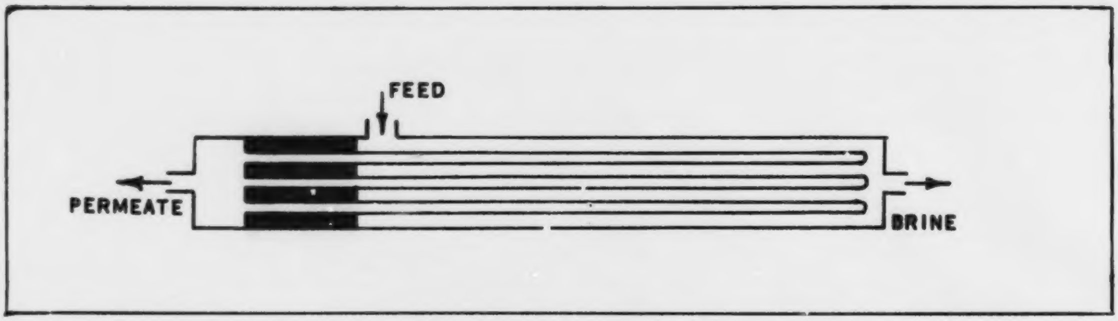

FEED
PERMEATE
BRINE

Figure 21. Simplied internal flow scheme, B-5 module

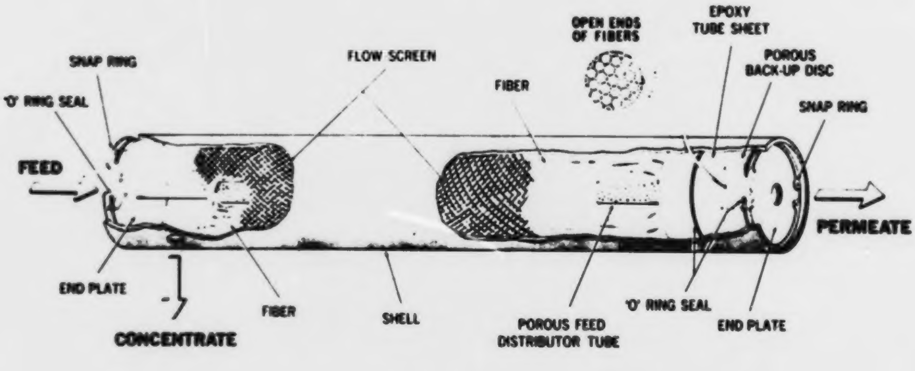

OPEN ENDS OF FIBERS
EPOXY TUBE SHEET
POROUS BACK-UP DISC
SNAP RING
FLOW SCREEN
FIBER
SNAP RING
'O' RING SEAL
FEED
PERMEATE
END PLATE
CONCENTRATE
FIBER
SHELL
POROUS FEED DISTRIBUTOR TUBE
'O' RING SEAL
END PLATE

Figure 22. Cut away drawing of B-9 permeator, (Courtesy, Du Pont)

Table 43. ESTIMATED MEMBRANE SURFACE AREA, DU PONT B-9's

Week of Modification	Estimated Surface Area
38	7,448 sq. ft.
53	8,424 sq. ft.
58	8,196 sq. ft.
63	7,920 sq. ft.

These areas were used in calculating the A values.

The manufacturer also stated that the B-9 modules would probably provide better flow distribution, permeability, less fouling tendency and significantly better solute rejection at a lower membrane cost per gallon than the B-5 modules. This claim will be commented on later.

Chronological Record

The following notes, abstracted from the plant data logs, list the major events and changes in operation for the Du Pont unit:

Week and Day

4	7	Placed in operation two B-5 permeators (Set 1A) on flow pattern "k". Ran on feed of reactor-clarified, sand and carbon filtered secondary effluent (with pre-R.O. unit chlorination and pH control).
7	5	Added D.E. filtration to feed treatment sequence.
18	6	Replaced the No. 2 B-5 permeator.
24	3	Feed treatment sequence reduced to reactor-clarification plus sand and activated carbon filtration.
33	7	Discontinued reactor-clarification of feed.
38	5	Replaced both B-5 permeators with five B-9 modules (Set IIA) using flow pattern "t".
41	4	After carbon filtration, add "pre-R.O. unit chlorination and pH adjustment.
49	4	Discontinued carbon filtration.
53	5	Replaced entire set of B-9 modules with new one (set IIB); initiated flow pattern "u". Operated temporarily using potable Colorado River water. Installed brine port venturies.
54	6	Resumed study using reactor-clarified, sand filtered, chlorinated, pH adjusted secondary effluent.
57	1	Reduced treatment sequence to sand filtration only (plus pre-R.O. unit chlorination and pH adjustment).
58	5	Replaced one permeator with B-9 module from used set IIA.
63	7	Replaced a second permeator with another module from set IIA.

64	3	Operated using untreated secondary effluent (pre-R.O. unit chlorination and pH adjustment excepted).
64	5	Removed venturies from brine ports.
66	4	Reduced product recovery; increased brine flow rate 100%.
67	2	Discontinued testing program.

Data Groupings

Twelve time periods were selected for comparison as shown in Table 44 with four additional consolidated groupings (weeks 8-23, 4-37, 38-53, 55-66) to facilitate comparison between specific and mixed process conditions.

Log A vs log time plots prepared for three of these groupings can be found in the latter part of this section.

Mechanical and Modular Problems

The Permasep® package experienced relatively few mechanical problems during the fourteen months it was tested. The mechanical problems consisted of a broken drive belt on the feed pump (week 51), alleged leaks in the epoxy tube sheets (set II A), and occasional malfunctions in the high-low pressure cut-out system. Most of the B-5 modular problems seemed to arise from one basic shortcoming in the unit design. Because the feed solution percolated both radially and longitudinally through the fiber bundle, it was hypothesized that there were regional flow differences within each permeator. It is assumed that the B-5 type, because of its longer length, was affected by regional flow differences more than the B-9 module.

Observations made during the testing period seem to support the poor flow distribution hypothesis. The second (downstream) series B-5 module suffered a permanent flux decline about week 16 in spite of Du Pont's prompt assistance and the use of a variety of cleansing solutions. While other R.O. makes required short periods of soaking (15-60 minutes) and flushing to restore normal fluxes, the Du Pont modules often required 12 to 24 hours of soaking for effective membrane rejuvenation. If the flow distribution was not uniform, it is likely that particulate solids became trapped within the bundle of fibers and prompted the longer soaking periods. Unlike the tubular cellulose acetate membranes, which tolerated feeds with moderate amounts of particulate solids, Du Pont designated that the feed to its unit pass first through Cuno 10 micron filters. After some major post secondary treatment processes were removed, a set of 40-50 micron filters were installed ahead of the 10 micron size to eliminate serious clogging of the fine mesh filters. Not only were the B-9 modules better able to handle particulate solids, but the unit was smaller and easier to handle and most importantly, the cost of producing a gallon of product was reduced (see Section XVI).

Between weeks 4 and 66, there were 10,372 available operating hours. The Du Pont unit operated for 9543 (92.01%) of these hours. The out-of-service record for the Du Pont unit is shown in Table 45.

Table 44. REVERSE OSMOSIS PROCESS INFORMATION, DU PONT

Week Nos.	(A=Reactor Clarifier) (B=Sand Filters) (C=Carbon Filters) (D=D.E. Filters) (E=Pre-R.O. Unit Chlorination) (F=pH Control)	Membrane Set	Flow Pattern	Special Conditions
4-7	A,B,C,E,F	IA	k	-
8-18	FULL (A,B,C,D,E,F)	IA	k	-
19-23	FULL	IA	k	Permeator Replacement
8-23	FULL	IA	k	-
24-33	A,B,C,E,F	IA	k	-
34-37	B,C,E,F	IA	k	-
4-37	VARIOUS	IA	k	-
38-41	B,C,E,F	IIA	t	-
42-48	A,B,C,E,F	IIA	t	-
49-53	A,B,E,F	IIA	t	-
38-53	VARIOUS	IIA	t	-
54	NONE	IIB	u	COLORADO RIVER WATER TEST
55-57	A,B,E,F	IIB	u	-
58-63	B,E,F	IIB	u	Permeator Replacement
64-66	E,F	IIB	u	Permeator Replacement
55-66	VARIOUS	IIB	u	-

Table 45. OUT-OF-SERVICE RECORD, DU PONT

	Hours			Total %
	B-5 &	B-9	Total	
Mechanical problems	-	-	163	1.57
Membrane cleaning	243	205	448	4.32
Membrane failures	-	-	-	-
Alterations, additions	-	-	116	1.12
Post-Secondary Trtmt. Prob.	-	-	102	.98
Total down time	243	205	829	7.99

Water Permeability Data

The average A values and GFD (gallon/sq.ft.-day) ratios shown in Table 46 should not be compared with similar values given for other units. In the hollow fiber concept, low flux ($gm/cm^2 x sec$) is offset by greater available membrane area.

The thirty-fold difference between B-5 and B-9 average A values illustrates why the Du Pont values are almost useless for comparison with those of other units.

The utility of the A values lies with how they vary with time as in the log A-log Time Plots. In Table 46 the slopes for B-5 and B-9 values are similar. There was only one period (weeks 24-33) when the slope turned positive, which in turn gave a low data correlation coeffient. The rejuvenation log sheets show that the No. 2 B-5 permeator was flushed four times with EDTA during that period. If a correlation exists between EDTA flushes and A values, then it can be assumed that there was significant scale buildup before the flushes. There seems to be no identifiable relationship between flux decline and post secondary effluent treatment until about week 58, when reactor-clarification was terminated and sand filtration only was used in post treatment of the secondary effluent. The flux then declined 40 per cent in five weeks. The flux declined 65 per cent while operating on minimally-treated feed (secondary effluent with chlorination and pH control) between weeks 64 and 66.

Water Recovery and Total Rejection Ratios

Tables 47, 48 and 49 show the feed product and brine water constituent concentrations. The Du Pont product water recovery ratios shown in Tables 50 and 51, are not temperature corrected, as opposed to the A value computations for which it is necessary to correct for temperature. The time periods are split to show differences (if any) between the B-5 and B-9 performances. Standard deviations for the recovery ratios and the estimated confidence levels are shown in Table 51.

Table 46. WATER PERMEABILITY DATA, DU PONT

Week Nos.	No. Data Sets	Avg. A x 10^5	Log-Log Slope	Std. Dev. Slope	Correl. Coeff.	Avg. G.F.D.	Average Effective Operating Pressure (P.S.I.)
4-7	14	0.008457	-0.0118	0.00760	.410	0.06102	462
8-18	50	0.007323	-0.0914	0.01426	.679	0.05284	543
19-23	25	0.006711	-0.0491	0.00661	.840	0.04842	552
8-23	75	0.007119	-0.0821	0.01069	.668	0.05136	530
24-33	47	0.006038	+0.0026	0.00250	.153	0.04356	560
34-37	21	0.005974	-0.0069	0.00282	.491	0.04310	552
4-37	157	0.006762	-0.0982	0.00692	.752	0.04879	543
38-41	13	0.302159	-0.0459	0.00831	.858	2.180	379
42-48	38	0.261217	-0.0179	0.00386	.612	1.885	363
49-53	19	0.219444	-0.0060	0.00551	.255	1.583	336
38-53	70	0.257481	-0.0813	0.00626	.844	1.858	358
54	6	0.255550	-0.0200	0.00766	.794	1.844	382
55-57	16	0.158479	-0.0875	0.00813	.945	1.143	378
58-63	29	0.111664	-0.0780	0.01528	.700	0.8057	367
64-66	13	0.062497	-0.0270	0.01147	.579	0.4509	365
55-66	59	0.113098	-0.2250	0.02472	.770	0.8160	370

Table 47. pH ADJUSTED FEED WATER QUALITY, DU PONT

		mg/l except spec. cond. as micromhos									
WEEK NOS.	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARD-NESS	ORTHO-P	ALKA-LINITY	CALCIUM	NO_3-N	SO_4
4-7	780.0	1222.2	–	12.40	13.60	-	–	-	-	-	–
8-18	686.4	1267.9	110.09	8.48	8.39	208.33	–	60.33	-	5.72	295.18
19-23	768.0	1256.3	121.01	9.28	6.55	211.11	3.59	43.66	58.88	3.97	223.12
8-23	711.9	1264.5	118.79	8.72	7.48	210.34	3.59	52.01	58.88	4.97	237.84
24-33	729.5	1250.1	137.04	5.87	4.57	200.11	6.99	32.10	52.73	5.50	322.58
34-37	761.2	1246.6	-	9.08	5.32	222.01	13.68	37.25	–	3.20	385.54
4-37	730.9	1253.5	126.56	8.09	6.28	207.81	7.36	42.63	54.49	4.90	312.95
35-41	815.0	1234.9	130.89	12.61	6.32	234.81	14.13	93.80	79.54	0.45	330.19
42-48	769.2	1215.6	129.92	7.59	-	236.98	7.24	70.19	72.58	5.19	335.63
49-53	813.0	1216.6	161.35	34.88	1.87	231.00	8.07	69.29	64.26	8.72	323.58
38-53	796.0	1218.1	143.24	15.50	8.10	237.29	9.25	75.81	67.69	6.04	329.33
54	821.0	1291.7	83.33	10.91	10.00	409.09	-	47.02	85.71	0.49	416.66
55-57	780.0	1248.1	137.46	36.30	23.68	229.05	8.96	68.87	61.54	6.61	339.80
58-63	805.8	1285.0	150.33	41.93	28.18	223.56	13.18	66.67	60.71	3.30	308.33
64-66	840.0	2020.9	148.87	49.13	31.90	234.15	12.56	98.00	64.12	5.86	337.58
55-68	807.9	1459.1	145.47	43.30	27.88	226.18	11.99	75.04	61.88	5.14	321.43
4-66	763.2	1285.2	137.69	16.61	8.61	223.87	9.07	67.18	63.36	5.11	324.32

Table 48. PRODUCT WATER QUALITY, DU PONT

				mg/l except spec. cond. as micromhos								
	WEEK NOS.	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARD-NESS	ORTHO-P	TOTAL ALKA-LINITY	CALCIUM	NO_3-N	SO_4
	4-7	277.5	529.2	-	8.10	11.20	-	-	-	-	-	-
	8-18	309.8	651.7	24.00	4.53	3.92	40.00	-	21.90	-	3.80	49.00
	19-23	269.0	549.0	102.25	4.88	3.10	53.20	1.08	11.70	13.43	3.25	20.75
	8-23	297.1	619.6	86.60	4.64	3.51	49.43	1.08	16.80	13.43	3.53	26.40
B-5	24-33	296.0	546.3	115.25	3.11	1.27	36.82	2.05	16.85	8.28	5.15	30.00
	34-37	265.0	548.5	-	4.07	1.68	35.30	3.67	23.17	-	1.60	32.00
	4-37	290.7	579.1	99.33	4.31	2.68	40.73	2.11	18.93	9.86	3.65	38.18
	38-41	55.0	102.5	7.33	4.27	1.10	7.28	0.44	37.52	7.00	0.07	17.50
	42-48	87.5	178.7	15.33	0.77	0.00	17.30	0.62	29.41	4.50	0.64	29.20
	49-53	110.0	205.6	22.75	1.50	1.80	23.10	0.88	38.94	6.04	1.70	39.80
	38-53	86.3	168.1	15.90	2.01	0.73	16.61	0.66	14.42	5.96	1.01	29.64
B-9	54	43.0	93.0	11.00	4.80	0.90	4.50	0.01	15.00	0.60	0.04	10.00
	55-57	85.0	132.3	15.67	5.30	0.90	7.33	0.49	33.47	1.60	1.50	17.33
	58-63	126.7	257.0	23.00	2.60	3.10	16.32	1.81	35.27	4.25	0.95	37.00
	64-66	196.7	608.3	46.00	7.47	5.20	28.80	1.86	45.47	6.73	2.43	79.67
	55-66	133.8	313.7	23.13	4.33	3.06	17.19	1.46	37.37	4.21	1.78	42.75
	4-66	207.0	416.4	44.61	3.79	2.27	26.64	1.37	31.17	6.70	2.32	36.00

Table 49. BRINE QUALITY, DU PONT UNIT

WEEK NOS.	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	TOTAL HARD-NESS	ORTHO-P	ALKA-LINITY	CALCIUM	NO_3-N	SO_4
			mg/l except spec. cond. as micromhos							
4-7	-	2781	-	-	-	-	-	-	-	-
8-18	-	3797	-	-	-	-	-	-	-	-
19-23	-	4778	202	56.7	-	67.0	-	-	5.1	-
24-33	2158	3822	222	16.1	717	46.6	94.8	193	1.8	-
34-37	2344	3166	-	22.5	761	48.0	39.5		2.3	-
4-37	2375	3779	222	28.1	734	48.2	70.2	193	2.7	-
38-41	2385	3500	449	22.3	834	47.0	220	216	6.4	800
42-48	2055	2988	370	23.1	674	20.2	184	203	10.3	872
49-53	1677	2419	278	63.0	514	17.0	140	138	18.9	716
38-53	2026	2937	374	29.2	674	-	179	172	11.4	756
54	2590	3097	334	35.0	1272	0.0	70.0	258	1.6	1481
55-57	1903	2833	321	59.0	567	20.0	57.7	154	18.0	828
58-63	1502	2256	234	70.5	456	24.5	136	127	9.7	584
64-66	1103	1791	203	59.3	358	20.0	71	-	8.1	-
55-66	1502	2330	263	64.9	459	22.3	100	141	10.4	735
4-66	1950	3271	295	37.2	641	31.6	127	174	5.7	822

Table 50. WATER RECOVERY AND TOTAL REJECTION RATIOS, DU PONT

	WEEK NOS.	WATER RECOVERY RATIO	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARD-NESS	ORTHO-P	ALKA-LINITY	CALCIUM	NO_3-N	SULFATE
B-5	4-7	.704	.644	.367	-	.347	.176	-	-	-	-	-	-
	8-18	.793	.549	.486	.782	.465	.533	.808	-	.636	-	.336	.834
	19-23	.790	.650	.563	.155	.474	.527	.748	.699	.732	.771	.181	.907
	8-23	.795	.583	.510	.271	.468	.531	.765	.699	.677	.771	.291	.889
	24-33	.770	.594	.563	.159	.470	.723	.818	.707	.475	.843	.064	.845
	34-37	.741	.652	.560	-	.551	.685	.841	.732	.378	-	.500	.917
	4-37	.771	.602	.538	.217	.468	.573	.804	.714	.556	.819	.256	.878
B-9	38-41	.684	.933	.917	.944	.661	.826	.969	.969	.600	.912	.844	.967
	42-48	.673	.886	.853	.882	.899	-	.927	.914	.581	.938	.876	.913
	49-53	.565	.865	.831	.859	.957	.931	.900	.891	.438	.906	.805	.877
	38-53	.642	.892	.862	.889	.870	.910	.930	.929	.546	.912	.832	.910
	54	.703	.946	.928	.868	.560	.910	.989	-	.681	.993	.918	.976
	55-57	.566	.891	.894	.886	.854	.962	.968	.945	.514	.974	.773	.949
	58-63	.515	.843	.800	.847	.938	.890	.927	.863	.471	.930	.712	.880
	64-66	.351	.766	.499	.691	.848	.837	.876	.852	.536	.875	.585	.764
	55-66	.487	.834	.735	.841	.900	.890	.904	.819	.502	.932	.653	.867
	4-66	.682	.729	.676	.676	.774	.736	.881	.847	.535	.870	.546	.897

Table 51. DU PONT WATER RECOVERY DATA

Weekly Period	Membrane Set	Average Recovery Ratio	Standard Deviation	No. Of Data Pts.	80% Confidence Level
4-7	IA	.704	.050	4	.62 - .79
8-18	IA	.793	.034	11	.75 - .84
19-23	IA	.799	.020	5	.77 - .83
24-33	IA	.770	.023	10	.74 - .80
34-37	IA	.741	.020	4	.71 - .77
38-41	IIA	.684	.027	4	.64 - .73
42-48	IIA	.673	.036	7	.62 - .72
49-53	IIA	.565	.016	5	.54 - .59
54	IIB	.685	-	1	-
55-57	IIB	.566	.034	3	.50 - .63
58-63	IIB	.515	.029	6	.47 - .56
64-66	IIB	.351	.161	3	.16 - .54

The standard deviations are uniformly low (except during the last three week period) and it would seem that the limits could have been logically set at about the 90% confidence level. During the final weeks of the study, severely fouled membranes produced erratic performance and incongruous data. There were only minor variations in the total rejection ratios before this period. The changes toward lower product water and higher solute rejection ratios after week 38 (after B-9 installation) reinforces the probability that the new membranes were "tighter". The observation that the recovery ratios decreased while A values increased would indicate an improvement in membrane efficiency. The total rejection ratios in Table 52 obtained through the courtesy of Du Pont, are based on a single day's performance of B-5 modules. The values check rather closely with the average data shown in Table 50 for weeks 19 through 23.

Table 52. SOME CONSTITUENT REJECTION DATA, COURTESY OF DU PONT

Constituent	Total Rejection Ratio
Ca	.83
Mg	.86
Na	.48
K	.53
SO_4	.83
PO_4	.69
Cl	.15
F	.37
SiO_2	.07

Average Rejection and Material Balance Ratios

The average rejection ratios uncorrected for temperature and material balance ratios in Table 53 show correlation with the degree of post secondary treatment. The material balance data are uniformly good (agree within plus or minus ten per cent). The exceptions are probably the result of sampling or analytical errors.

Membrane Fouling and Cleansing

The Du Pont unit exhibited marked fouling tendencies and required frequent and prolonged membrane rejuvenations. Many types of cleaning solutions were tried, either singly or in combinations (reversed flow, high and low pressure flushings, air bumps, extended soaking periods, etc.) without, in most cases, a substantial or permanent improvement in the flux. The manufacturer worked very closely with the plant operator in suggesting new techniques, materials, etc. and assisted in their application.

A partial list of the chemicals and materials used, includes weak acetic acid, Proctor & Gamble's "Biz", citric acid, dilute hydrochloric acid, EDTA (as the tri-sodium salt), weak caustic soda, sodium hexa-metaphosphate, sulfamic acid, etc., and even a Du Pont proprietary product termed "Chemical X" (possibly tannic or formic acid).

The membranes were flushed or cleansed about ninety times in fourteen months of operation. During the last months of the study, the flushing frequency was increased to every other day. An inclusive list of rejuvenations, divided for convenience into the three permeator service periods, is found in Tables 54 through 56.

Because the flux increases were based only on data obtained before and after rejuvenation, there is no indication of the duration of improvement. However, during the final weeks, the improvements were short lived, lasting not much more than a day. For a more complete picture of membrane cleansing procedures, the reader is referred to Appendix A-3.

Comments

Some permeators were removed and returned to the manufacturer for inspection. The fibers were reported to be in excellent condition without evidence of over-chlorination or deterioration across the bundle. It is the manufacturer's opinion that higher (perhaps 3 fold) chlorination dosages could have been tolerated, but only if applied using a contact chamber with a 30 minute detention time. Although the membrane material was in good condition, internal modular fouling was noted.

The examination report on the B-5 module No. 2 removed at week 18, stated that the unit was partially fouled with inorganic deposits, "about 95% calcium phosphate and sulfate." In a report on a spent B-9 module, two types of fouling were cited. A crystalline deposit of calcium sulfate was found on modules arranged in the "five-in-parallel" pattern. No

Table 53. AVERAGE REJECTION AND MATERIAL BALANCE RATIOS, DU PONT UNIT

	Week Nos.	Average Rejection Ratios						Material Balance Agreement Ratios					
		T.D.S.	Spec. Cond.	Total C.O.D.	Total Hard-Ness	Ortho-P	NO_3-N	T.D.S.	Spec. Cond.	Total C.O.D.	Total Hard-Ness	Ortho-P	NO_3-N
B-5's	4-7	.767	.747	-	-	-	-	.912	1.034	-	-	-	-
	8-18	.816	.735	-	-	-	-	1.071	1.005	-	-	-	-
	19-23	-	.800	.805	-	.855	.333	-	1.028	1.405	-	.888	.883
	8-23	.816	.755	.805	-	.855	.333	1.071	1.012	1.405	-	.888	.883
	24-33	.798	.775	.681	.912	.840	.168	.955	.985	1.068	.982	1.004	1.007
	34-37	.828	.736	.746	.928	.880	.850	1.052	.938	1.015	1.003	1.140	1.824
	4-37	.806	.758	.723	.919	.850	.380	.988	.998	1.131	.990	1.026	1.180
B-9's	38-41	.967	.956	.748	.986	.985	.973	1.022	.948	.907	1.084	1.079	3.712
	42-48	.938	.916	.947	.962	.954	.928	.938	.919	.933	.983	.999	.825
	49-53	.912	.887	.968	.939	.932	.878	.972	.962	.758	1.021	.993	.822
	38-53	.937	.917	.891	.961	.955	.919	.972	.,940	.885	1.020	1.017	1.305
	54	.976	.967	.792	.995	-	.963	1.063	.925	1.310	1.060	-	1.115
	55-57	.935	.933	.888	.984	.966	.878	1.107	.973	.834	1.148	1.014	1.231
	58-63	.885	.851	.957	.945	.900	.815	.956	.923	.846	.990	1.002	.961
	64-66	.802	.747	.862	.900	.884	.656	.964	.985	.832	1.019	1.043	1.044
	55-66	.877	.845	.918	.939	.914	.746	.995	.951	.840	1.030	1.016	1.048
	4-66	.877	.818	.822	.945	.888	.735	.985	.974	.971	1.010	1.019	1.730

Table 54. MEMBRANE REJUVENATION RECORD, DU PONT B-5's

(WEEKS 4-37)

Type	No. Of Times	Average Flux Increase (%)
Air bump	11	5
Acetic acid	1	0
Biz	18	8
"Chemical X"	1	0
Dilute HCl	1	0
EDTA	11	9
Total	43	Average 6%

Table 55. MEMBRANE REJUVENATION RECORD, DU PONT B-9's

(WEEKS 38-53)

Type	No. Of Times	Average Flux Increase (%)
Biz	7	4
EDTA	7	2
Total	14	Average 3%

Table 56. MEMBRANE REJUVENATION RECORD, DU PONT B-9's

(WEEKS 55-66)

Type	No. Of Times	Average Flux Increase (%)
Biz	16	15
EDTA	8	5
Biz-EDTA	5	4
Other	6	0
Total	35	Average 8%

deposits of similar constituency were found on the modules involved in the 3-2 pattern. All of the modules which were in service at week 66 were heavily plugged with organic slime. What these observations indicate is the superior nature of the 3-2 flow pattern "t". Using flow pattern "t", the flow rate was great enough to prevent buildup of inorganic scale, and there was no need to install venturies to maintain high brine pressures. Without venturies, the organic deposit problem might have been reduced if not eliminated. When the "t" pattern was finally resumed, it was too late to be effective on the severely fouled modules.

Du Pont also had other helpful comments which are condensed below:

1. Du Pont type permeators are not likely to be highly successful using feeds with high total and dissolved C.O.D. or large amounts of colloidal material.
2. The minimum advisable secondary effluent post-treatment would be sodium hexa-metaphosphate (to inhibit calcium sulphate precipitation) followed by sand filtration, chlorination (with adequate contact time) and ten micron cartridge filtration.
3. Automatic dumping and flushing controls are needed in the event of power failures: (this would be helpful in preventing supersaturated solutions from depositing their solutes during a pressure drop or a pH change).

A Value - Time Plots

Three A vs time (hours) plots were prepared:

Figure 23 - weeks 4-37
Figure 24 - weeks 38-53
Figure 25 - weeks 55-66

The discontinuity in Figure 23 occurring at 2107 hours (week 18) resulted when the second B-5 permeator was replaced by a new module. The discontinuity in Figure 25 at 1373 hours (week 64) indicates the effect of discontinuing sand filtration and operating the unit on chlorinated, pH adjusted (only) secondary effluent.

Colorado River Water Test

In order to obtain R.O. data on very high calcium, high sulfate water, the second set of B-9 modules were initiated using Colorado River Water. The test conditions were:

Five B-9 permeators in parallel;
Venturi type pressure controlling orifices close to the shell on the exit line from each permeator, as suggested by the manufacturer;
Total membrane area - 8,424 sq. ft.;
Average pressure in psi:
Inlet - 407.7; Brine (at shell) - 372.2;

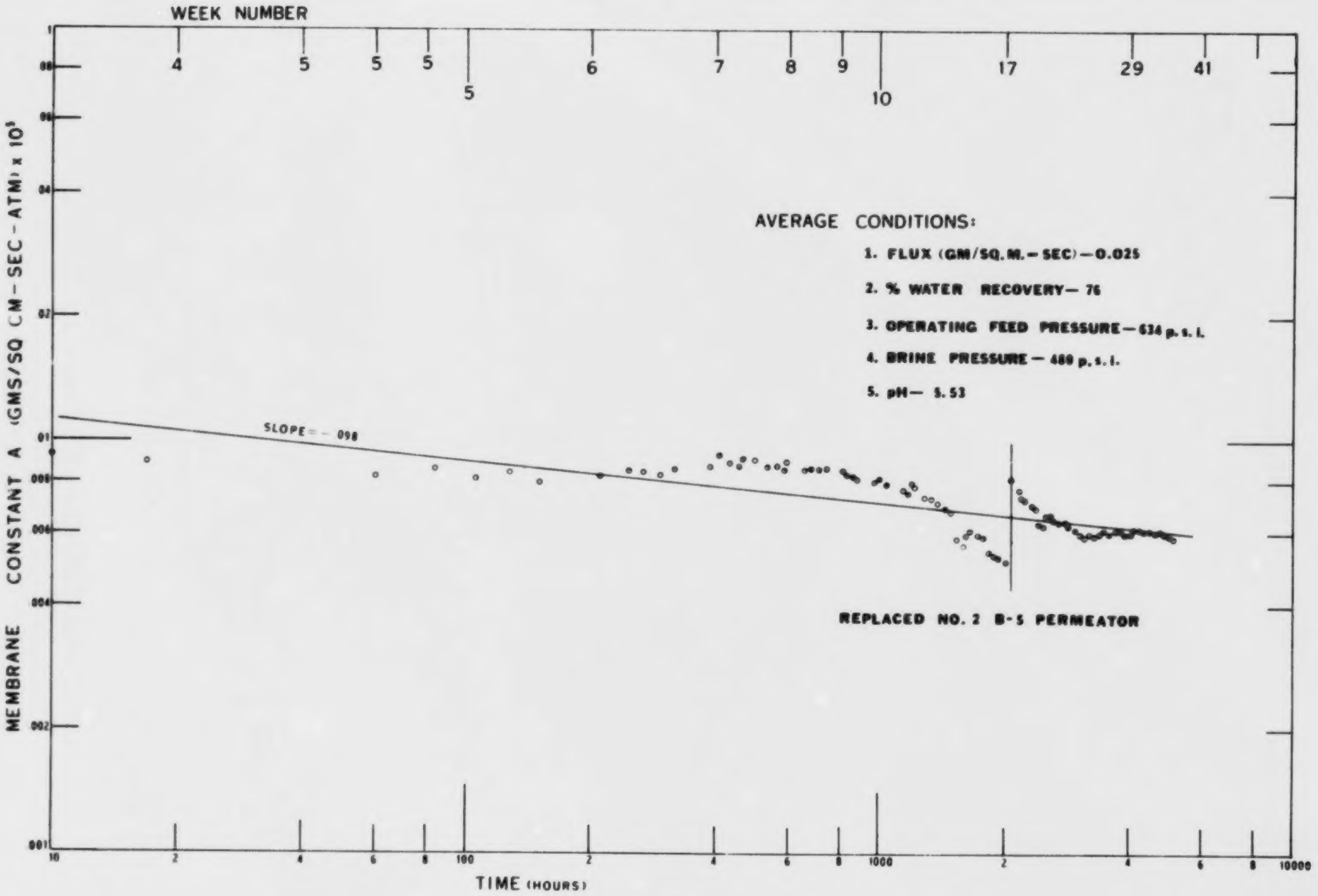


Figure 23. A vs. Time plotted logarithmically, DuPont, 3/27/70 - 11/13/70 (B-5's)

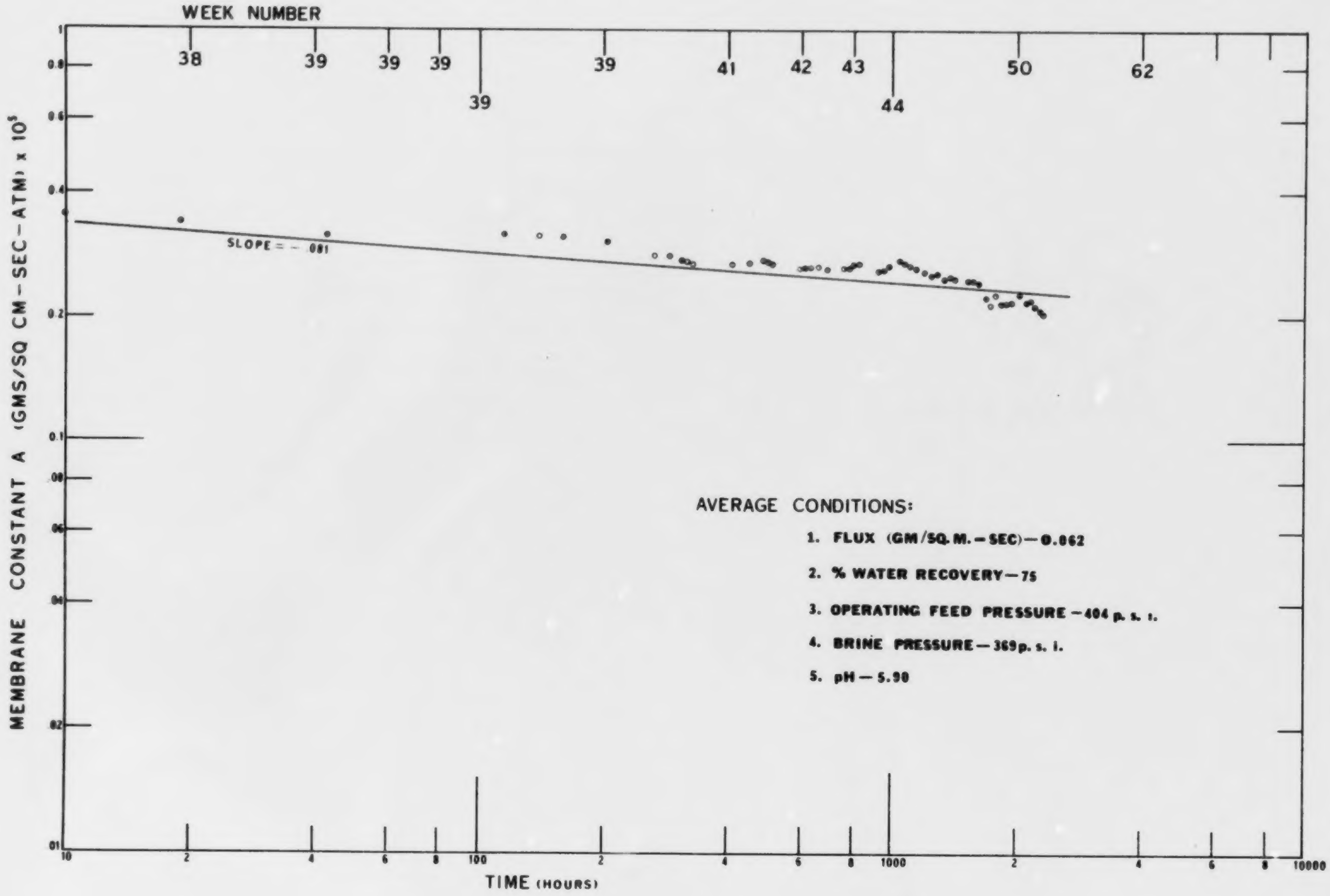


Figure 24. A vs. Time plotted logarithmically, Du Pont 11/18/70 - 3/2/71 (B-9's)

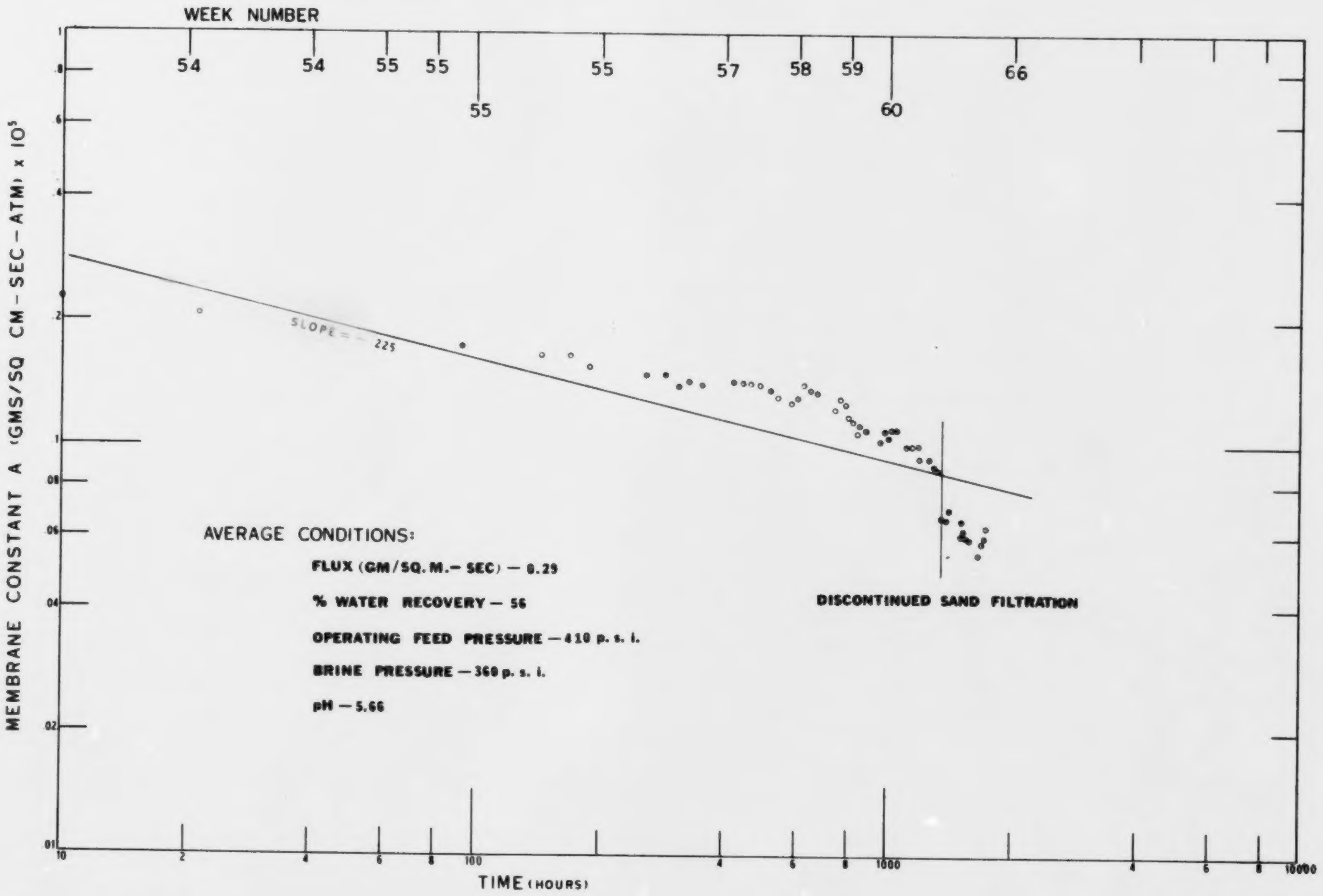


Figure 25. A vs. Time plotted logarithmically, Du Pont, 3/11/71 - 6/4/71 (B-9's)

Inlet feed temperatures 57 to 60 degrees (F);
Feed pH - 6.0
Average total feed flow rate (for the five modules) - 8.8 gpm.

After adjusting to 25° C, the physical test data averaged:
Recovery ratio - 0.912
A value - 0.256×10^{-5} gm/sq. cm-sec-atm

The chemical data and the total rejection ratios are shown in Table 57:

Table 57. DU PONT B-9 PERMEATOR ANALYSES

COLORADO RIVER WATER TEST RUN (mg/l)

Constituent	Acidified Feed	Product	Total Rejection Ratio
Na	124	18	.85
K	7	0	-
Ca	88	0.5	.99
Mg	37	0.7	.98
Cl	102	13	.87
Nitrate-N	0.43	0.08	.81
SO_4 (Raw = 336)	436	11	.97
Ortho-P	0.04	0.04	-
Total P	0.04	0.04	-
Total C.O.D.	11.0	4.8	.56
Diss. C.O.D.	9.7	0.9	.91
Total Hardness	372	4.0	.99
T.D.S. (Raw 752)	822	47	.94
Si	7	1	.85
B	0.4	0.3	.25
Fe	0.02	0.00	-
Mn	0.00	0.00	-
F	0.5	0.3	.40

SECTION XII

GULF GENERAL ATOMIC UNIT, SPIRALLY WOUND MODULE DESIGN

Introduction

This unit was purchased from Gulf General Atomic Incorporated of San Diego, California. (In late 1970 the corporate name was changed to Gulf Environmental Systems Company). The unit's characteristic component is its spirally wound module. The six modules making up the unit were rated by the manufacturer at a nominal capacity of 10,000 gallons per day, with 60% product water recovery and about a 0.90 rejection ratio.

Physical Configuration

Figure 26 is a photograph of a Model 5016 Gulf reverse osmosis unit as used in this study. The six ten ft. long pressure vessels in the left background, house the spirally wound modules; the three vessels in the foreground contain three multistage series-connected submersible centrifugal pumps. The polyethylene container at the left is a sulfuric acid make-up tank for pH control of the feed.

Within each pressure vessel were three-3 foot long Model 4000 modules connected in series. The feed was distributed to the first three pressure vessels in parallel. The two following vessels received (in parallel) the combined brine flows from the first three vessels. A final vessel received the combined brine flows from the latter two. This configuration is designated as pattern "m" (3-2-1), with eighteen modules for an overall effective membrane area of 900 sq. ft. (based on the nominal membrane area of 50 sq. ft. per module).

The unit had a nominal total rejection ratio of about 0.945 when operating on a 2000 mg/l sodium chloride solution at 600 psi and 25° C.

The product water flow rate, over the lifetime of the unit, was estimated by the manufacturer to be 8.3 gal./sq.ft./day when no "major" membrane fouling conditions existed. (Note: this would give the unit an average capacity of about 7500 gal./day). At a 0.60 recovery ratio, and a 95% time-on-line factor, the brine flow was estimated at about 3.6 gpm.

No Reynolds numbers were estimated for the Gulf unit but it was the manufacturer's opinion that at brine flows below 2.5 gpm, concentration polarization accompanied by a severe fouling was possible. There was relatively little other mechanical equipment description supplied by the manufacturer.

Membrane Specifications

The manufacturer stated that the membrane used in the Model 4000 Gulf

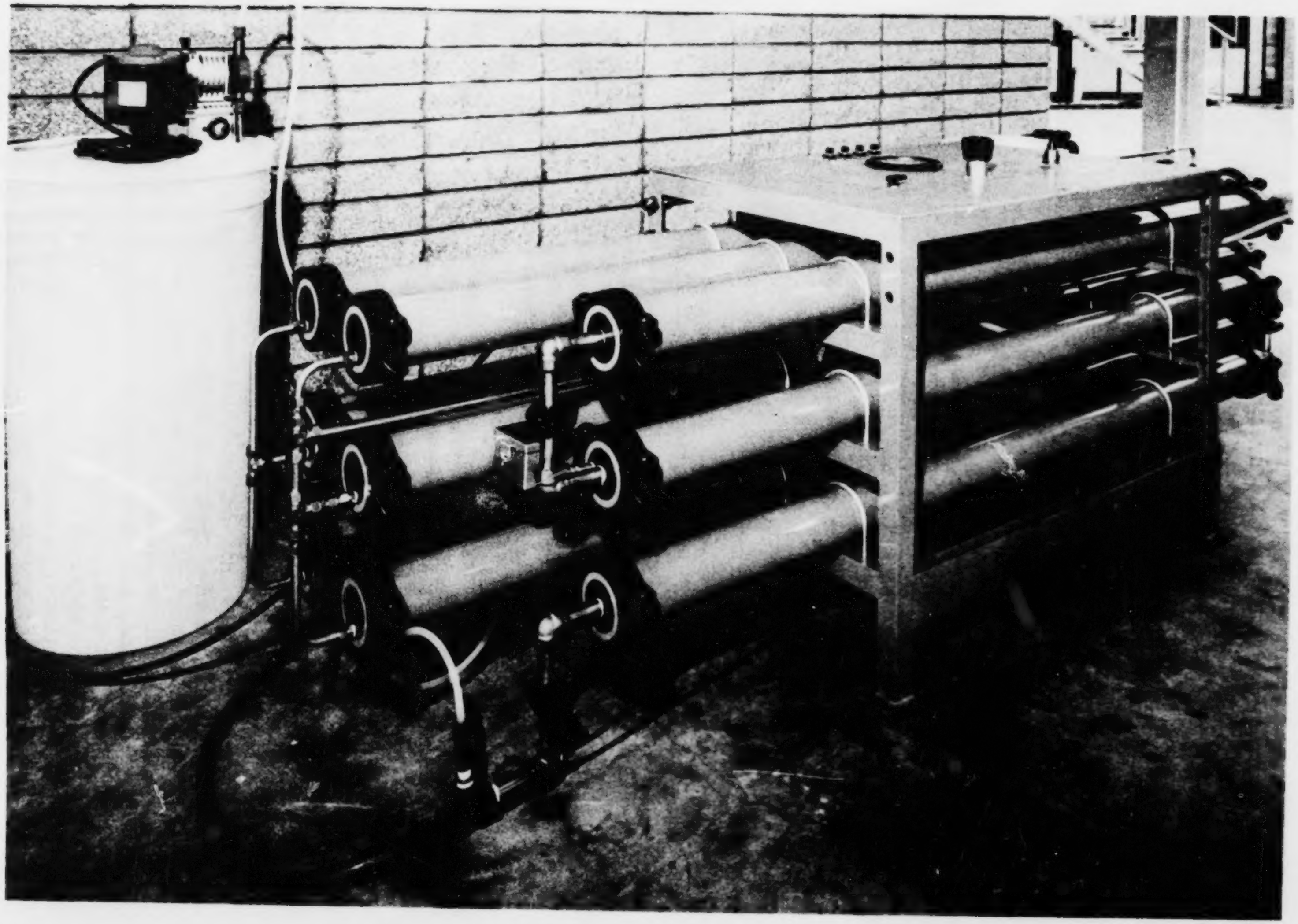


Figure 26. Gulf General Atomic Inc. reverse osmosis unit

module was made from "...cellulose acetate (Eastman chemicals) processed by a modified Loeb technique. (It is) asymmetric (with a) dense surface layer 1000-2000 Angstrom units thick and a more spongy support 3-4 mils thick..." In a second communication, it was stated that the "...membrane contains approximately two-thirds water by weight and is cast on a drum from commercial grades of cellulose acetate, described as a 2.5 acetate with an acetyl content of approximately 39 to 40%. After casting, the membrane is annealed for a short time at 80 to 85°C..."

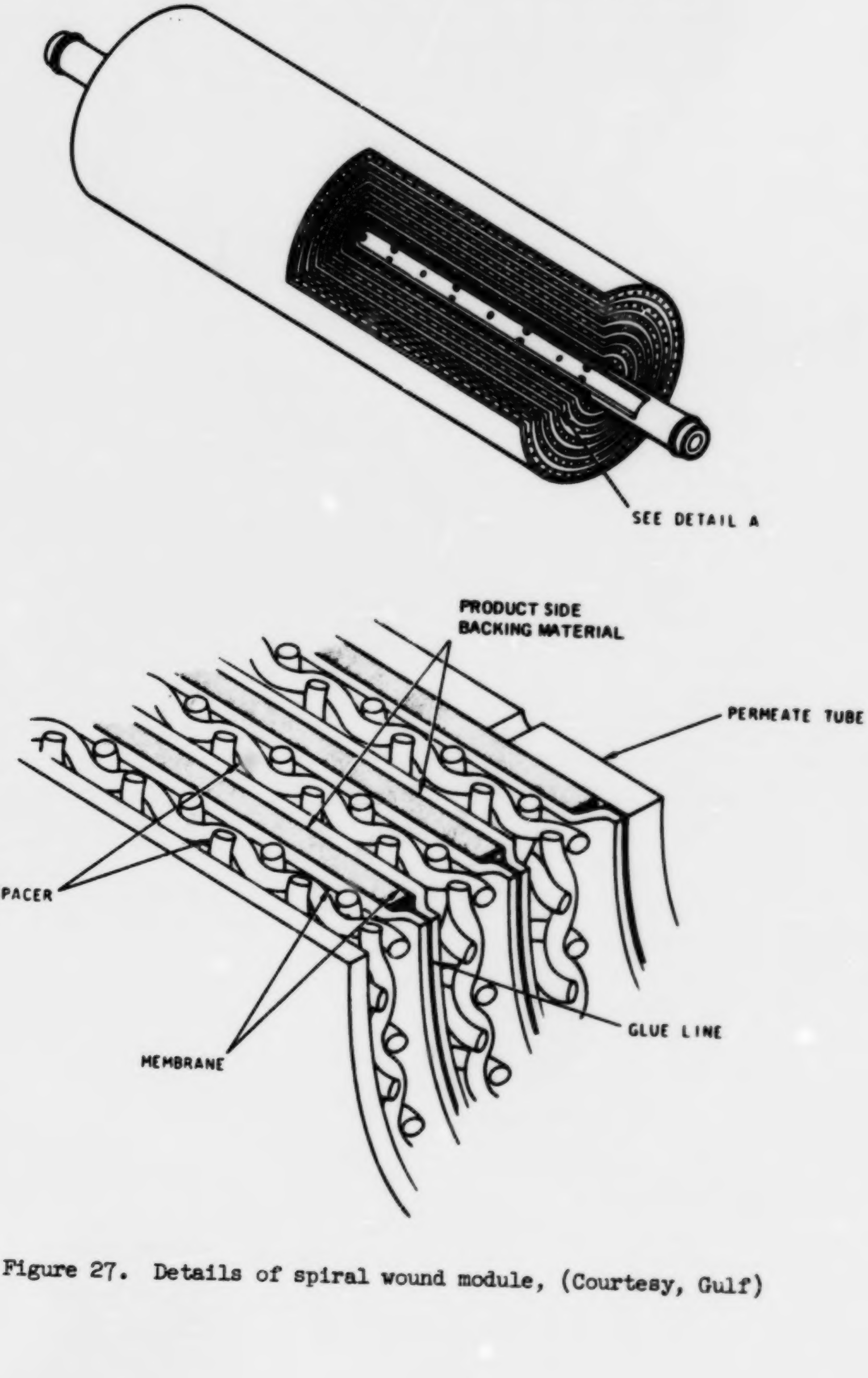
They also stated that "... in the sets of modules ... tested (at Hemet), the membrane was supported by a backing of D-601 polyester sailcloth..."

In Gulf's "SP3214-13A 0106910" product bulletin, it is stated that the membranes plus the backing material are used to form a sandwich. After sealing, this envelope and a mesh backing material are wound around a perforated plastic tube to form the spiral module. Figure 27 illustrates.

Chronological Record

The following notes, taken from the plant data logs, show the major events and changes in operation:

Week and Day		
2	4	Unit placed in operation. Membrane Set No. 1, flow pattern "m". Unit operating on feed of secondary effluent, treated by reactor-clarification, sand and activated carbon filtration. pH adjustment also included.
5	4	Added pre-R.O. unit chlorination to feed treatment sequence.
7	6	Began D.E. filtration - feed of reactor-clarified, sand, activated carbon and D.E. filtered secondary effluent followed by pre-R.O. unit chlorination and pH adjustment.
24	3	Stopped D.E. filtration of feed.
31	3	Shut unit down - pump failure.
32	6	Restarted unit after pump failure.
33	6	Removed reactor-clarification. Feed treatment: sand and granular activated carbon filtration followed by pre-R.O. unit chlorination and pH control.
41	4	Resumed reactor-clarification at head of secondary post treatment sequence.
46	4	Removed activated carbon filters; feed consisting of reactor-clarified, sand filtered secondary effluent with pre-R.O. unit chlorination and pH control.
48	6	Shut unit down - feed pump failure.
49	6	Restarted unit with new (No. 2) membrane set installed. Feed: reactor-clarified, sand filtered, pre-R.O. unit chlorinated, and pH adjusted secondary effluent.
50	1	Shut unit down - feed pump failure.
50	7	Feed pump restarted.
57	6	Feed treatment: sand filtered secondary effluent with chlorination and pH control.



DETAILS OF SPIRAL WOUND MODULE CONSTRUCTION

SEE DETAIL A
PRODUCT SIDE BACKING MATERIAL
PERMEATE TUBE
MESH SPACER
GLUE LINE
MEMBRANE

Figure 27. Details of spiral wound module, (Courtesy, Gulf)

Week and Day		
64	3	Shut unit down - feed pump failure.
66	6	Restarted unit using pre-R.O. unit chlorinated and pH adjusted secondary effluent.
69	7	Stopped testing program.

Data Groupings

The data groups shown in Table 59 were selected primarily to emphasize the effect of changes in feed quality on reverse osmosis performance. Two consolidated sets, for weeks 2-48 and 49-69, were included to show the average operating conditions for the two Gulf membrane sets used during the study. Because these consolidated periods include mixed process conditions, their data may not compare well with that of other groups. The primary purpose was to group data which appear in the Gulf log A time plots.

Mechanical and Operational Problems

Of the mechanical equipment, only the Reda multistage submersible centrifugal pumps gave any serious problems during the test period. The three series-connected pumps (Figure 26) were mounted with their individual motors inside pressure vessels similar to those housing the spirally wound membranes.

Conduction to the surrounding water was the only means to dissipate heat generated by the 2 H.P., 230 volt motors which may have been the prime cause of pump failure. Although these pumps were repaired or replaced without charge by the manufacturer, their numerous failures (9 times over 69 weeks) broke the continuity of testing and very likely contributed to membrane fouling. It is difficult to separate the "mechanical" pump problems from those termed as "operational". The latter group normally includes membrane fouling and membrane flushing difficulties and frequencies, but in this instance difficulties could be the result of poor circulation, changes in the mode of treatment or even the inherent flow characteristics of the spirally wound module.

Between weeks 2 and 69, there were 11,594 available operating hours. The Gulf unit operated for about 86% of this time (10,016 hours). Table 58 lists the major out-of-service hours and the percentages they represent.

Table 58. OUT-OF-SERVICE RECORD, GULF UNIT

	Hours	%
Mechanical problems	1233	10.64
Membrane cleaning	129	1.11
Membrane failures	-	-
Alterations, additions	16	.14
Pretreatment feed problems	200	1.72
Total down time	1578	13.61

Table 59. REVERSE OSMOSIS PROCESS INFORMATION, GULF

Week No.	Secondary Post-Treatment	Membrane Set	Flow Pattern
2-3	A,B,C,F	1	m
4	A,B,C,F	1	m
5-6	A,B,C,E,F	1	m
7	A,B,C,E,F	1	m
8-23	A,B,C,D,E,F	1	m
24-33	A,B,C,E,F	1	m
34-41	B,C,E,F	1	m
42-46	A,B,C,E,F	1	m
47-48	A,B,E,F	1	m
2-48	VARIOUS	1	m
49-57	A,B,E,F	2	m
58-63	B,E,F	2	m
49-69	VARIOUS	2	m
66-69	E,F	2	m

Post-Treatment Legend

A = Reactor-Clarification
B = Sand Filtration
C = Activated Carbon Filtration
D = D.E. Filtration
E = R.O. Unit Chlorination
F = pH Control

Water Permeability Data

The Gulf A values and similar related ratios are shown in Table 61. Data for week 4 are shown separately to emphasize the effect of the first Biz flushing. If data for weeks 2-4 were grouped together, A value data would appear (erroneously) continuous to week 34.

At week 34 (4863 hours on Figure 29), the A values fell abruptly when the reactor-clarifier was shut down. The A values continued at a low level even after resuming reactor-clarification at week 42 (6102 Hours). This would suggest that the membrane irreversibly fouled in the absence of reactor-clarification.

The use of the D.E. filters during the 8-23 weekly period did not change water permeability. This agrees with observations made on the other units. The A value again declined sharply, when the activated carbon filters were removed at week 47. During the final weeks of the study, the log A-log time slope became relatively steep indicating a loss of permeability and accelerated membrane fouling.

The low data correlation coefficient in the 42-46 weekly grouping can be correlated to a very low log-log slope ratio. The same is true, to a lesser degree, for the 24-33 weeks' set. Both conditions can be related to effective membrane rejuvenation toward the end of the grouping.

Water Recovery and Total Rejection

Tables 62, 63 and 64 show the constituent concentrations in the R.O. feed, product water and brine. The total rejection ratios in Table 65 vary slightly except for a few random points which may be the result of sampling or analytical errors. Standard deviations for the recovery ratios and the estimated confidence levels are shown in Table 60. The standard deviations are uniformly low in most instances and confidence levels correspondingly narrow except during the early periods (reflecting high initial membrane compaction rate) and during the intense fouling conditions after week 49.

Table 60. GULF WATER RECOVERY DATA

Weekly Period	Membrane Set	Average Recovery Ratio	Standard Deviation	No. Of Data Pts.	80% Confidence Level
2-3	1	.475	.066	2	.27 - .68
2-7	1	.502	.059	4	.40 - .60
8-23	1	.678	.050	16	.61 - .74
24-33	1	.696	.024	10	.66 - .73
34-41	1	.623	.037	8	.57 - .68
42-46	1	.565	.052	5	.48 - .64
47-48	1	.482	.011	2	.45 - .52
49-57	2	.586	.101	9	.44 - .73
58-63	2	.402	.086	6	.28 - .53
66-69	2	.290	.034	4	.23 - .35

Table 61. WATER PERMEABILITY DATA, GULF

Week Nos.	No. Data Sets	Avg. A x 10^5	Log-Log Slope	Std. Dev. Slope	Correl. Coeff.	Avg. G.F.D.	Avg. Effective Op. Pressure(P.S.I.)
2-3	8	0.9829	-0.0514	0.0101	.902	7.09	539
4	4	1.2443	-0.0272	0.0209	.677	8.98	570
5-6	12	0.9330	-0.0248	0.0117	.556	6.73	592
7	5	1.1273	+0.0140	0.0131	.525	8.13	596
8-23	79	1.0079	-0.0429	0.0048	.717	7.27	579
24-33	39	0.9313	+0.0042	0.0049	.138	6.72	580
34-41	35	0.8251	-0.0442	0.0051	.831	5.95	584
42-46	24	0.7676	-0.0006	0.0041	.030	5.54	593
47-48	11	0.5918	-0.0271	0.0172	.465	4.27	601
2-48	217	0.9190	-0.0806	0.0077	.579	6.63	581
49-57	37	0.9258	-0.1941	0.0155	.904	6.68	541
58-63	31	0.5377	-0.1095	0.0278	.591	3.88	582
49-69	83	0.6946	-0.2807	0.0183	.863	5.01	559
66-69	15	0.4485	-0.0702	0.0210	.679	3.24	561

Table 62. FEED WATER QUALITY, GULF, pH ADJUSTED

mg/l except spec. cond. as micromhos

WEEK NOS.	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARD-NESS	ORTHO-P	ALKA-LINITY	CALCIUM	NO_3-N	SO_4
2-3	760.0	1222.7	-	28.75	-	-	-	-	-	-	-
4-7	750.0	1215.2	-	22.36	23.53	-	-	-	-	-	-
8-23	740.3	1283.8	118.70	8.83	7.27	200.0	3.07	35.56	58.82	4.36	360.0
24-33	737.8	1252.7	142.47	5.88	4.55	200.0	6.90	40.12	51.57	4.00	314.3
34-41	778.8	1253.1	136.23	10.85	5.73	221.67	13.64	54.20	66.66	0.741	340.0
42-46	762.5	1200.0	120.25	8.28	1.30	227.50	7.50	26.05	-	-	363.6
47-48	792.5	1329.3	134.72	31.15	22.40	262.00	6.92	41.34	67.65	6.60	388.8
2-48	752.7	1253.2	130.14	11.49	7.99	138.93	8.18	41.59	55.62	4.37	339.0
49-57	795.7	1288.8	137.36	35.08	25.71	230.00	8.18	26.12	76.17	7.63	345.0
58-63	840.0	1246.1	150.26	42.35	27.91	225.29	13.38	59.15	66.69	5.90	416.6
66-69	846.7	1365.9	116.79	44.00	15.93	216.43	8.83	15.45	72.70	4.31	496.7
49-69	821.9	2000.0	154.41	60.62	61.40	259.23	12.80	44.92	54.17	2.66	333.3
2-69	770.8	1304.5	134.65	19.56	10.29	223.75	9.25	39.98	58.94	2.87	347.3

Table 63. PRODUCT WATER QUALITY, GULF

(mg/l except spec. cond. as micromhos)

WEEK NO.S	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARD-NESS	ORTHO-P	TOTAL ALKA-LINITY	CALCIUM	NO_3-N	SO_4
2-3	70.0	134.5	-	2.300	-	-	-	-	-	-	-
4-7	80.0	96.0	-	2.750	1.200	-	-	-		-	-
8-23	48.0	95.0	14.60	0.362	0.640	2.00	0.046	16.43	2.000	2.272	3.60
24-33	72.8	114.0	16.67	0.711	0.414	3.80	0.069	19.98	1.083	2.450	4.40
34-41	69.4	142.6	22.75	2.050	0.700	3.99	0.147	21.68	2.000	0.280	2.38
42-46	85.0	151.2	19.00	2.533	1.100	5.46	0.090	18.44	-	-	4.00
47-48	87.5	163.5	26.00	2.150	2.150	6.55	0.090	18.85	1.150	4.250	3.50
2-48	65.6	117.8	19.00	1.275	0.759	3.89	0.090	19.30	1.446	2.438	3.39
49-57	56.4	103.1	12.50	6.700	0.900	2.30	0.090	10.29	0.457	3.800	4.14
58-63	65.8	94.7	29.00	1.567	1.200	3.83	0.428	13.84	1.067	2.700	5.00
49-69	73.3	112.0	19.27	3.564	1.625	3.03	0.256	12.24	0.727	2.803	4.47
66-69	63.1	158.0	21.00	4.850	3.500	3.37	0.320	15.05	0.650	1.360	4.00
2-69	65.0	116.1	19.12	1.702	0.864	3.58	0.148	16.83	1.061	2.548	3.82

Table 64. BRINE QUALITY, GULF

WEEK NOS.	T.D.S.	SPEC. COND.	mg/l except spec. cond. as micromhos				ALKA-LINITY	CALCIUM	NO_3-N	SO_4
			CHLORIDE	TOTAL C.O.D.	TOTAL HARD-NESS	ORTHO-P				
2-3	-	1925	-	-	-	-	-	-	-	-
4-7	-	2289	-	-	-	-	-	-	-	-
8-23	-	3802	344	38.2	-	7.4	-	-	7.8	-
24-33	2370	4318	453	15.1	704	52.7	55.0	190	5.3	-
34-41	2011	3167	330	19.1	620	38.1	71.9	176	9.5	750
42-46	1720	2550	319	18.0	555	15.2	40.8	-	12.0	-
47-48	1592	2490	256	55.5	523	13.9	50.5	146	7.9	-
2-48	1962	3368	349	23.4	599	32.5	54.3	173	7.7	750
49-57	1736	2802	281	62.9	506	18.7	27.6	138	16.3	812
58-63	1304	2073	204	69.1	422	21.6	36.1	111	6.3	625
66-69	1030	1664	-	67.7	305	14.3	28.6	-	4.1	-
49-69	1526	2332	252	66.7	449	19.1	31.0	129	9.4	750
2-69	1794	3082	312	35.6	535	27.6	44.6	147	7.7	750

Table 65. WATER RECOVERY AND TOTAL REJECTION RATIOS, GULF

WEEK NOS.	WATER RECOVERY RATIO	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	DISS C.O.D.	TOTAL HARD-NESS	ORTHO-P	ALKA-LINITY	CALCIUM	NO_3-N	SULFATE
2-3	.475	.908	.890	-	.920	-	-	-	-	-	-	-
4-7	.502	.893	.921	-	.877	.949	-	-	-	-	-	-
8-23	.648	.935	.926	.877	.959	.912	.990	.985	.538	.966	.479	.990
24-33	.696	.901	.909	.883	.879	.909	.981	.990	.502	.979	.388	.986
34-41	.623	.911	.887	.833	.811	.878	.982	.989	.600	.970	.622	.993
42-46	.565	.889	.874	.842	.694	.154	.976	.988	.392	-	-	.989
47-48	.482	.890	.877	.807	.931	.904	.975	.987	.544	.983	.356	.991
2-48	.618	.913	.906	.854	.889	.905	.982	.989	.536	.974	.442	.990
49-57	.586	.929	.920	.909	.809	.965	.990	.989	.606	.993	.502	.988
58-63	.402	.922	.924	.807	.963	.957	.983	.968	.766	.983	.542	.988
66-69	.290	.913	.918	.835	.919	.898	.986	.971	.208	.990	.349	.991
49-69	.466	.923	.921	.864	.920	.943	.987	.975	.665	.988	.490	.988
2-69	.574	.916	.911	.858	.913	.916	.984	.984	.579	.982	.461	.989

Average Rejection and Material Balance Ratios

The average rejection and material balance ratios shown in Table 66 are important as accuracy indicators for the sampling and analytical methods used in this study. The material balances show data agreements generally within plus or minus ten per cent (total C.O.D. and nitrate nitrogen ratios excepted) which agrees well with data from other units.

Membrane Fouling and Cleansing

The Gulf modules were flushed one hundred times with various cleansing solutions. This very high frequency, when compared with similar data for the other units, is probably the result of poor flow distribution within the spirally-wound modules.

The Gulf unit cleansings are arranged in Table 67 according to feed treatment. This type of presentation was used because of the relatively consistent operational conditions, not possible with the other units.

Table 67 indicates that membrane rejuvenations were most effective when operating on the least treated feed. These data are misleading, however, when it is realized that most of the improved post-rejuvenation fluxes lasted less than twenty-four hours.

The membrane fouling problem was discussed on numerous occasions with the manufacturer and most of the flushing techniques and changes in the solution compositions were used at their suggestion. At one time they suggested that a principal foulant might be aluminum salts carry-over from the reactor-clarifier. At no time, however, did the reactor-clarifier operate without subsequent sand or activated carbon filtration. Additionally, post-reactor-clarifier samples were analyzed numerous times and at no time did the aluminum content exceed 0.12 mg/l. Most of the samples contained no detectable aluminum. Analyses of two "spent" flushing solutions of weak phosphoric acid also indicated minute retention of aluminum by the modules.

Particulate fouling, however, was probably the major cause of poor fluxes experienced during the latter stages of this study. It was speculated that because of the module design, the membrane or module acted as a filter for the insoluble constituents. Once particulate buildup began, the fluxes became gradually worse, especially with poor feed quality. Indeed, Gulf mentions in a training handbook, "... the spiral module is not adapted to the treatment of water containing a high degree of particulate matter. If suspended solids... are introduced... a slow buildup of particulate matter... may result." Besides particulate matter, other constituents (i.e. dissolved organics) were considered as possible foulants of the Gulf modules.

Since slime had been found in some of the other unit modules, it was speculated that humic acid from the slime may have dissociated at pH's below 5.0. Although the feed pH did drop slightly below 5.0 on two abbreviated occasions towards the end of the study, there was no apparent correlation with the A values (indicators of flux).

Table 66. AVERAGE REJECTION AND MATERIAL BALANCE RATIOS, GULF UNIT

	Average Rejection Ratios						Material Balance Agreement Ratios					
Week Nos.	T.D.S.	Spec. Cond.	Total C.O.D.	Total Hard-Ness	Ortho-P	NO_3-N	T.D.S.	Spec. Cond.	Total C.O.D.	Total Hard-Ness	Ortho-P	NO_3-N
2-3	-	.920	-	-	-	-	-	.983	-	-	-	-
4-7	.883	.942	-	-	-	-	.852	.883	-	-	-	-
8-23	.959	.959	.971	-	.994	.579	1.653	.978	2.595	-	1.130	.907
24-33	.960	.954	.923	.990	.995	.638	1.062	.974	.932	1.117	1.042	1.064
34-41	.950	.931	.858	.990	.994	.884	1.012	.932	.953	1.028	1.078	2.400
42-46	.926	.916	.752	.985	.992	-	.946	.941	1.123	.956	.955	-
47-48	.926	.909	.951	.984	.992	.402	1.098	.935	.964	1.069	1.174	.926
2-48	.944	.944	.902	.988	.994	.580	1.044	.956	1.303	1.036	1.050	1.148
49-57	.955	.951	.860	.994	.994	.671	1.030	.935	1.003	1.041	1.018	1.190
58-63	.933	.940	.979	.984	.969	.557	.923	.962	.907	1.010	.950	.914
66-69	.923	.930	.919	.988	.972	.366	.951	.957	.687	.943	.953	1.315
49-69	.941	.943	.933	.989	.981	.550	.975	.948	.915	1.014	.982	1.186
2-69	.943	.944	.910	.989	.989	.567	1.016	.954	1.197	1.028	1.023	1.165

Table 67. GULF RECORD OF MEMBRANE REJUVENATION

	Biz	EDTA	Biz & EDTA	H_3PO_4	HCl	HOCl	Mixture
Post Treatment Sequence: (A=Reactor Clarifier) (B=Sand Filters) (C=Carbon Filters) (D=D.E. Filters) (E Pre-R.O. Unit Chlorination) (F=pH Control)							(sodium perborate Tritox X-100 Carboxymethyl cellulose solution)
A,B,C,D,E,F No. Flushes/37 weeks	22	31	4	-	11	-	-
Avg. % Flux Increase	8	6	4	-	8	-	-
B,C,D,E,F No. Flushes/8 weeks	2	2	4	-	-	-	-
Avg. % Flux Increase	4	7	8	-	-	-	-
A,B,E,F No. Flushes/11 weeks	17	1	1	2	5	-	-
Avg. % Flux Increase	18	3	11	9	1	-	-
B,E,F, No. Flushes/6 weeks	15	-	-	-	5	-	-
Avg. % Flux Increase	14	-	-	-	8	-	-
E,F, No. Flushes/3 weeks	3	-	-	-	-	2	1
Avg. % Flux Increase	45	-	-	-	-	40	45
Totals No. Flushes/68 weeks	59	6	9	2	21	2	1
Avg. % Flux Increase	17.8	5.3	7.7	9	5.6	40	45

As mentioned early, it was the manufacturer's contention that low brine flows (below 2.5 gpm) could result in membrane fouling. Between weeks 18 and 69, there were thirty-four days in which this occurred. Thirty-three of these values were in the range of 2.20 to 2.45 gpm, while the thirty-fourth was recorded at 1.95 gpm. These "sub-critical" brine flows cannot be given full credit for fouling, as heavy fouling symptoms (weeks 51 to 69) do not correlate entirely with the general period in which the low flows and reduced Reynolds Numbers occurred. A third likely contributor to fouling was inadequate chlorination of the unit feed. Without sufficient chlorination, bacterial slime buildup on the membrane may occur readily, irrespective of modular design. High nutrient values of the feed would accelerate the slime growth rate. (See Section VII for the discussion of "Membrane Fouling and Cleansing.")

Comments in Retrospect

Gulf has indicated that some of the procedures used in this project were inappropriate to their unit. Among these "faults", was the policy of gradually reducing the feed treatment. The other was an alleged low chlorine residual in the feed.

Comments to the above follow:

1. The general impact of using a gradually worsening quality of feed was recognized in the planning stages and ample opportunity to voice disapproval with the program format was given. With intentions clearly stated, the decision was made to proceed with all units (irrespective of design) operating under very similar conditions. One to be tested was the spiral wound design module. Thus, the Gulf unit, as used in this project was primarily representative of the spirally-wound design and secondarily representative of Gulf Environmental and its results should be viewed similarly.

2. With respect to the "low" residual chlorine maintained in the feed, it is pertinent to quote a number of communications from the manufacturer.

   From a letter dated September 12, 1969,
   "... as a recommended pretreatment procedure for your unit, it will be necessary to adjust the pH of the feed to about 5 and to maintain a chlorine residual of about 1 mg/l..."

In the manufacturer's specific operating instructions, which were received somewhat later, it was said that:

> "...If the feedwater does not consistently contain at least 0.2 ppm Cl_2 residual, continuous chlorine addition at a level of 0.2 to 0.7 ppm should be considered..."

This would give a range of 0.2 to 0.9 mg/l.

Again, in a letter dated December 11, 1969, it was stated,

> "... if the feed is to be chlorinated continuously, the maximum recommended chlorine residual is 1 mg/l..."

Although the above comments represent three separate attitudes towards chlorination of feed, the feed maintained in this pilot study conformed remarkably well to these specifications. Therefore, the chlorine levels which were alleged to be so low as to allow slime growth on the membrane were in actuality within the guidelines set by Gulf.

A Value - Time Plots

Figures 28 and 29 show the log-log A value - time (in hours) plots for the two Gulf membrane sets. Figure 28 shows the data for the period from week 2 to 48. The abrupt rise in A at about 200 hours (week 3) shows the effect of the first Biz flush. The sharp decrease in A which levels off about 734 hours (week 6) appears to be the result of the second Biz flush. Up to the time of the second Biz cleaning, the unit was flushed seven times with a pH 5.0 water solution. It is evident that these acidic water solutions were ineffective. The effect of the reactor-clarifier shutdown which was discussed earlier under sub-section "Water Permeability Data", appears at 5300 hours (week 34). The abrupt decline in A at about 7000 hours, (week 47) is probably the result of discontinuing granular activated carbon filtration.

All of the data shown in Figure 29 were obtained using the second set of modules. The carbon filters were not in service during any portion of this period and this probably caused the steep slope. Three feed pump failures at weeks 63 and 64 (1916 to 2027) necessitated turning the unit off until week 67 when a new feed pump was installed. The unit was restarted on chlorinated pH adjusted secondary effluent.

The erratic data between 1800 and 3000 hours in Figure 29 is probably the result of pump failures plus efforts to keep the modules free of deposits.

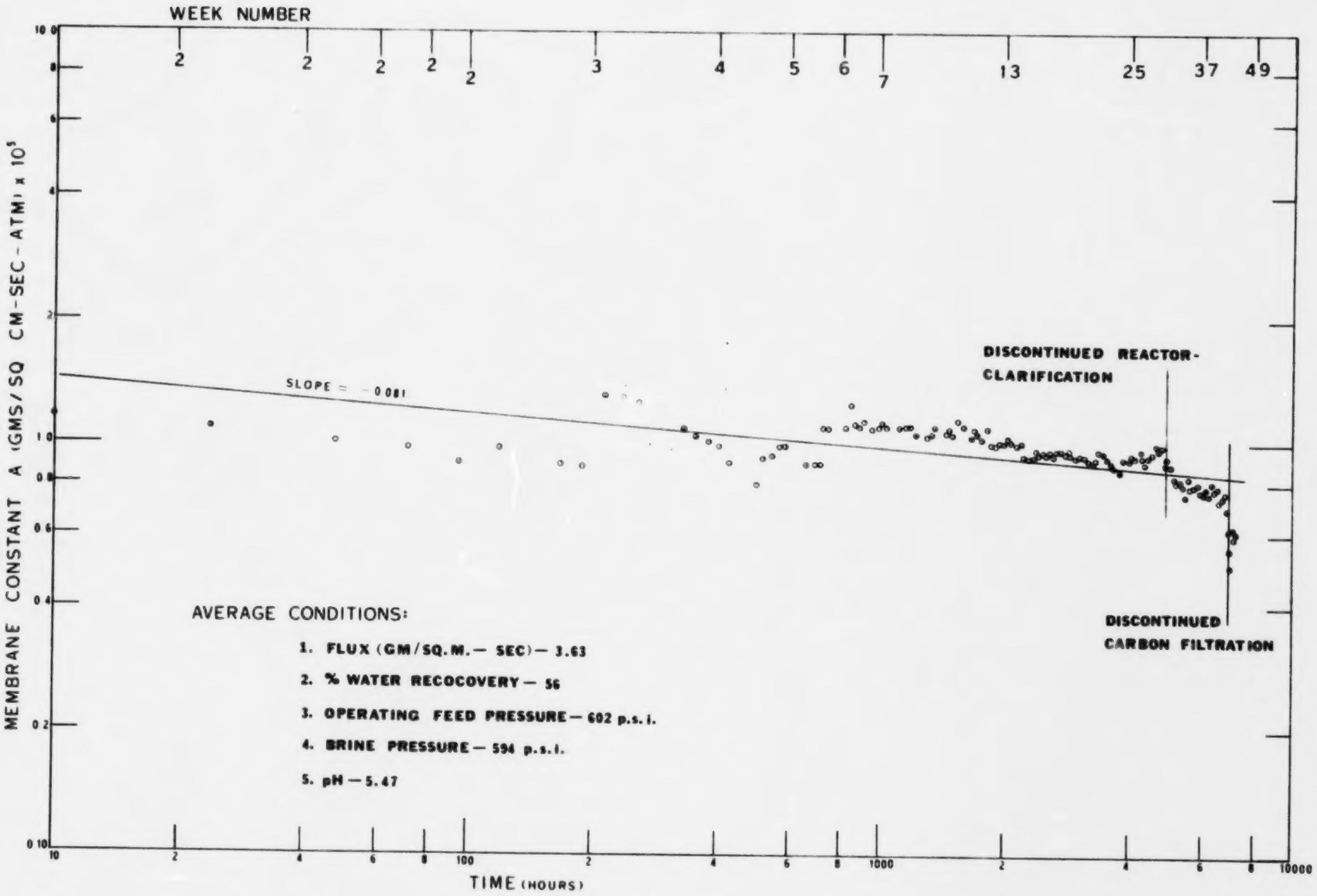


Figure 28. A vs. Time plotted logarithmically, Gulf, 3/9/70 - 1/27/71

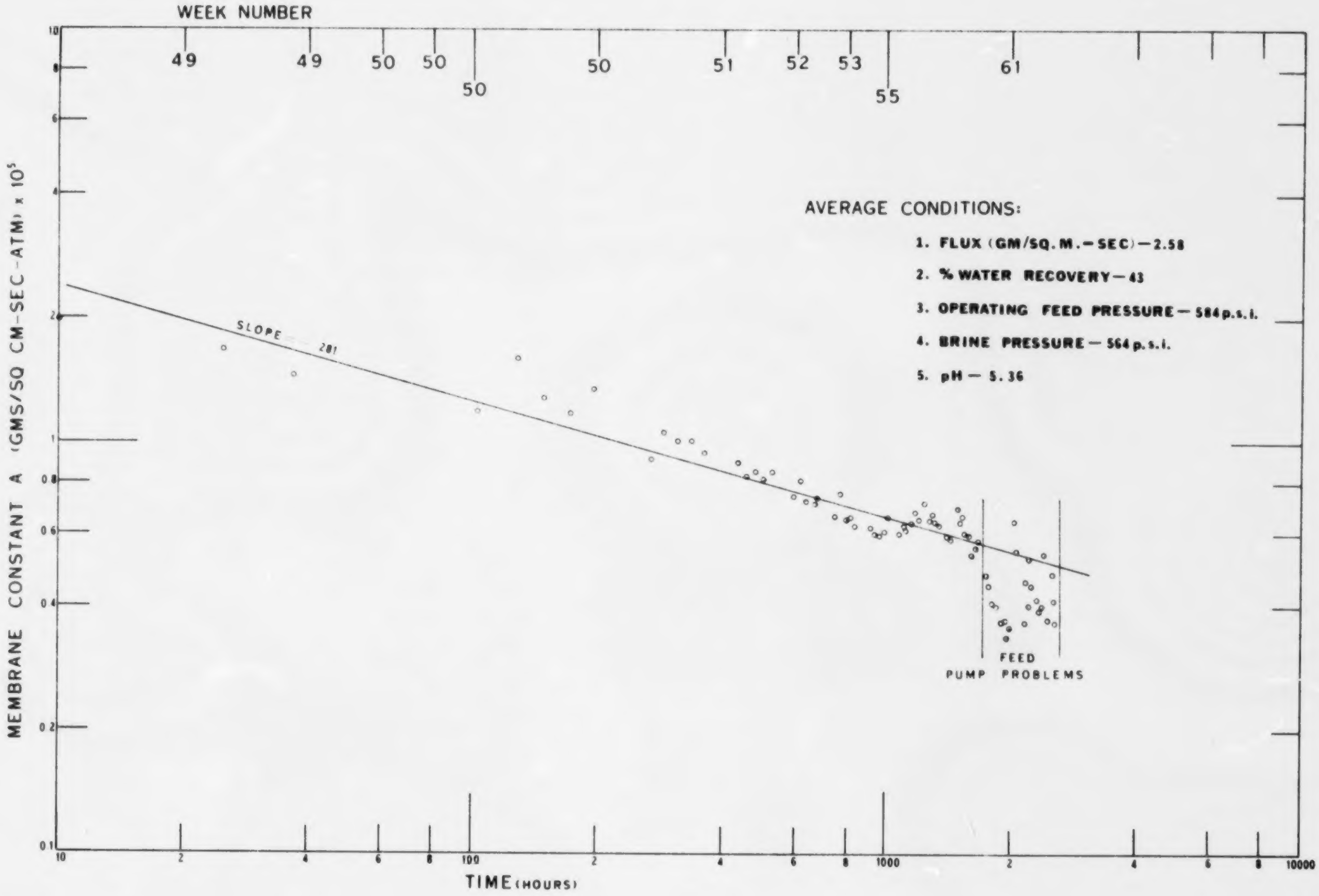


Figure 29. A vs. Time plotted logarithmically, Gulf, 2/4/71 - 6/25/71

SECTION XIII

RAYPAK INCORPORATED REVERSE OSMOSIS UNIT, MODIFIED TUBULAR DESIGN

Introduction

This unit was obtained at no cost to the project from the Ecological Systems Division of Raypak, Incorporated of El Cajon, California, later relocated to Westlake Village, California. This unit was substituted for the Aerojet General unit, removed in December of 1970.

Its nominal rating was given as about 3,000 gallons of product water per day at about a 50% product water recovery. Solute rejection was quoted as 90%.

Physical Configuration

The unit which was designated as ROpak Model 003004-03 consisted of eight parallel sets of modules (cells). Each set (bank) was made up of four series-connected modules. Within each module were four sets of two tubes (cores). A single tube was half the length of the module, and therefore, two tubes were joined end to end to form a complete module. The cellulose acetate membrane was on the outside surface of the axially-positioned tube sets. The thirty-two modules had a total surface area of 128 sq. ft.

From the above information and the manufacturer's statement that the tubes occupied half of the modular cross section, it was calculated that the tubes were about 0.64 in. O.D., the modules about 1.3 in. I.D. with hydraulic radius about 0.08 in.

Only one flow pattern, designated as "o" was used. This flow pattern was an eight parallel, four series modular arrangement. The Reynolds Number was estimated as about 7,000 for one of the better days of operation of this unit.

Membrane Specifications

Specific details of the membrane type were not available from the manufacturer. It was implied that the membrane was basically similar to the type used on the Universal unit, i.e. a cellulose acetate, formamide modified film as developed by Loeb and Manjikian at U.C.L.A., with a 0.90 total rejection ratio.

Chronological Record

Negotiations preliminary to the acquisition of the Raypak unit began about week 40. The manufacturer initially indicated delivery to be about week 47, but delivery problems along with other delays arose and the equipment did not arrive until week 50. The first unit leaked badly. A replacement unit was installed, but it too leaked badly so new modules were installed at week 62. The first set of process data was obtained in the latter part of week 62. The unit was shut down permanently at week 67. Throughout its five week period of operation, the unit ran without pH adjustment at the manufacturer's suggestion.

Data Groupings and Water Permeability Data

The Raypak process information and water permeability data are shown in Tables 68 and 69. Both the calculated A values and the data correlation coefficients were low throughout the testing period.

Table 68. REVERSE OSMOSIS PROCESS INFORMATION, RAYPAK

Week Nos.	Treatment	Membrane Set	Flow Pattern	Special Conditions
62-63	B, E	1	o	No pH Control
64-67	E	1	o	"
62-67	Various	1	o	"

Table 69. WATER PERMEABILITY DATA, RAYPAK

Week Nos.	No. Data Sets	Avg. A x 10^5	Log-Log Slope	Std. Dev. Slope	Correl. Coeff.	Avg. G.F.D.	Avg. Eff. Op. Press. (P.S.I.)
62-63	9	0.7922	-0.0156	0.1097	.054	5.72	754
64-67	18	0.5571	-0.1137	0.0739	.359	4.02	799
62-67	27	0.6355	-0.1202	0.0716	.318	4.58	790

Mechanical and Operational Problems

The Raypak unit had three main problems: (1) Plastic inserts which connected the tubes to the tube sheets at the end of the modules leaked badly, (2) the feed pump was of insufficient capacity and (3) the membrane area was too small.

The feed pump was rated at 5.6 to 5.9 gpm. After the pilot plant study was completed, the manufacturer stated that it should have been at least 15 gpm and that the Reynolds Number should have been about 20,000.

Water Recovery, Rejection Ratios and Product Water Analyses

Performance summary data are shown in Tables 70-74. The actual water recovery ratios are far below the design estimate of 0.50 even though the unit was operated within the 700-800 psi pressure range recommended by the manufacturer. Most other R.O. units were maintained in the 500-600 psi range.

Instead of the estimated 3000 gal./day of product water, the actual rate was never higher than 1100 gpd and averaged less than 605 gal./day.

During the six week test period the product recovery ratio averaged 0.0913 and the standard deviation was very nearly the same figure. With the single exception of the nitrate nitrogen ratio, most of the other solute total rejection ratios were close to the anticipated 0.90 value.

The material balance agreement ratios, in Table 74, were uniformly close to unity. This indicates that the reported low recovery ratios were valid and that the basic problem was not associated with erroneous data, but with basic design deficiencies in the Raypak unit.

Membrane Fouling and Cleansing

The membranes of the Raypak unit were cleansed eleven times during its six week testing period. Various flushing solutions were used, some of which caused the product flow rate to nearly double. It was usually only a few hours, however, until the flow rate returned to its original level.

The rate of fouling in the Raypak study seems abnormally high compared to other units. In all fairness to the Raypak unit, it should be mentioned that the feed to which the Raypak unit was exposed had high fouling potential, and this probably accounts in part for the rapid fouling. Likely fouling contributors include low circulation rate, tight packing of the tubes, and perhaps, the basic modular design feature of having the membrane supported from the inside.

A Value - Time Plots

Figure 30 shows the log-log A vs time (in hours) plot for the Raypak unit. The extreme heterogeneity of the data is evident and requires no further comment.

Table 70. pH ADJUSTED FEED WATER QUALITY, RAYPAK

(mg/l except spec. cond. as micromhos)

WEEK NOS.	T.D.S.	SPEC. COND.	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARD-NESS	ORTHO-P	TOTAL ALKA-LINITY	CALCIUM	NO_3-N	SULFATE
62-63	645.0	1295.8	44.44	-	218.42	11.84	265.71	62.50	6.19	156.25
64-67	748.8	1880.4	53.57	31.67	230.00	12.37	256.66	64.28	5.40	166.66
62-67	728.0	1686.7	53.87	31.67	230.95	12.28	259.88	63.80	5.56	161.76

Table 71. PRODUCT WATER QUALITY, RAYPAK

(mg/l except spec. cond. as micromhos)

WEEK NOS.	T.D.S.	SPEC. COND.	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARD-NESS	ORTHO-P	TOTAL ALKA-LINITY	CALCIUM	NO_3-N	SULFATE
62-63	30.0	155.5	0.40	-	8.30	0.45	18.60	2.00	1.40	5.00
64-67	75.0	833.0	8.25	8.33	32.85	1.87	49.28	8.10	2.95	2.00
62-67	66.0	607.2	6.68	8.33	27.94	1.58	43.14	5.86	2.64	2.75

Table 72. BRINE QUALITY, RAYPAK

mg/l except spec. cond. as micromhos

WEEK NOS.	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	TOTAL HARD-NESS	ORTHO-P	ALKA-LINITY	CALCIUM	NO_3-N
62-63	730	1334	122		250	14.6	269	-	5.9
64-67	777	1312	149	40	261	13.6	252	-	6.2
62-67	768	1319	136	40	259	13.8	257	-	6.2

Table 73. WATER RECOVERY AND TOTAL REJECTION RATIOS, RAYPAK

WEEK NOS.	WATER RECOVERY RATIO	T.D.S.	SPEC. COND.	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARD-NESS	ORTHO-P	TOTAL ALKA-LINITY	CALCIUM	NO_3-N	SULFATE
62-63	.039	.953	.880	.991	-	.962	.962	.930	.968	.774	.968
64-67	.104	.900	.557	.846	.737	.859	.849	.808	.874	.454	.988
62-67	.091	.909	.640	.876	.737	.879	.871	.834	.908	.525	.983

Table 74. AVERAGE REJECTION AND MATERIAL BALANCE RATIOS, RAYPAK

WEEK NOS.	AVERAGE REJECTION RATIOS						MATERIAL BALANCE AGREEMENT RATIOS					
	T.D.S.	SPEC. COND.	TOTAL C.O.D.	TOTAL HARD-NESS	ORTHO-P	NO_3-N	T.D.S.	SPEC. COND.	TOTAL C.O.D.	TOTAL HARD-NESS	ORTHO-P	NO_3-N
62-63	.956	.882	-	.965	.966	.769	1.089	1.017	-	1.098	1.200	.923
64-67	.904	.564	.881	.856	.864	.552	1.003	1.013	.911	.996	1.033	1.250
62-67	.917	.670	.881	.878	.885	.596	1.024	1.014	.911	1.016	1.066	1.184

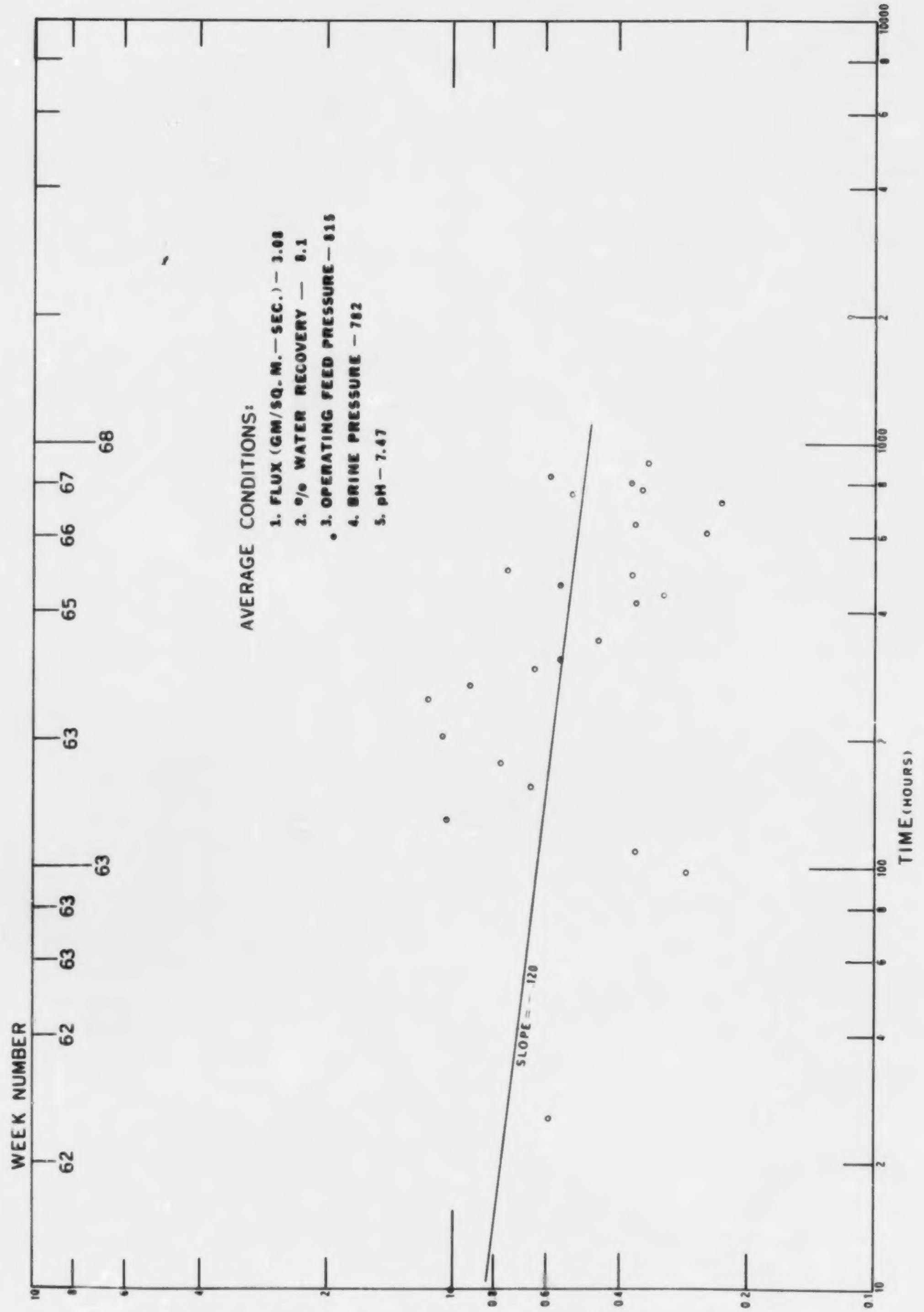


Figure 30. A vs. Time plotted logarithmically, Raypak, 5/6/71 - 6/14/71

SECTION XIV

UNIVERSAL WATER CORPORATION REVERSE OSMOSIS UNIT, A TUBULAR DESIGN

Introduction

This unit was obtained on a monthly rental basis from the Universal Water Corporation of San Diego, California. Its nominal capacity, with a full complement of seventy-two modules, was rated by the manufacturer at 10,000 gallons of product water per day.

The symbolic nomenclature and equations used in this section are listed and discussed in Sections V, VIII, and in the Appendix Section A-1.

Physical Configurations

The unit, as first placed in operation (shown in Figures 31 and 32), consisted of two identical vertically-mounted banks of nine horizontal racks with four modules on each rack. Each module contained eighteen series-connected 0.4 in. I.D. tubes, and there was 7.0 sq. ft. of membrane area per module.

Figure 7 shows an idealistic schematic flow diagram for a Universal unit. Although the drawing indicates the principal lines and control points, it varies from the configuration tested at Hemet in at least two important points:

1. It shows only two pressure accumulators. Up to three were required to control the pressure pulsations of the test unit.
2. A flow configuration wherein two banks of five racks in parallel were followed by four racks in parallel was not tested in this project.

The four flow patterns used on the Universal unit are listed and identified by letter below.

"p" - Flow was split between two identical banks (of racks) of modules. Within a bank the flow was first distributed, in parallel, to four sets of modules, (a set consisted of four serially-connected modules). The combined brine from the latter, was distributed in parallel to 3 more sets of modules in parallel. The brine from these was distributed to two final sets in parallel. Between the two banks there were 72 modules. At 7 sq. ft. per module the complete unit membrane area was 504 sq. ft. Membrane sets 1 and 4 were used in this configuration.

"q" - Two banks, of four parallel sets, each set with four modules in series. The total nominal area was 224 sq. ft. (thirty-two modules). Membrane set No. 2 was used in this flow configuration which was termed the high flux "open" type.

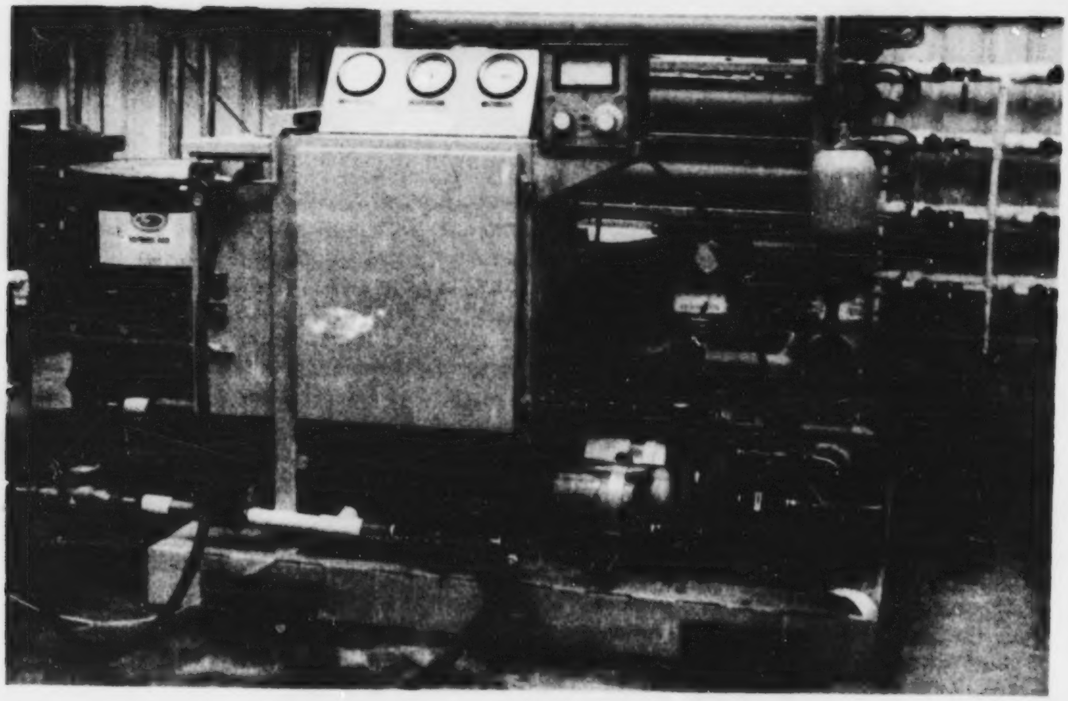
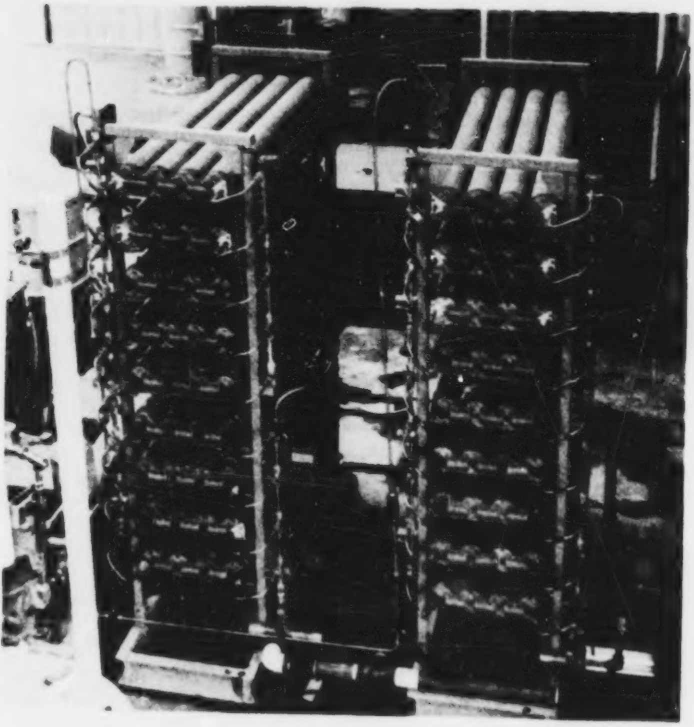


Figure 31. Universal Water Corp. reverse osmosis unit

Figure 32. Universal reverse osmosis unit in part



"r" - Two banks, each containing two sets of modules in parallel, followed by two sets of modules in series. Total nominal area (thirty-two modules) was 224 sq. ft. Membrane Set No. 2 was used in this flow configuration.

"s" - Two banks, each with two sets in parallel (each set containing eight modules in series). Total nominal area (thirty-two modules) was 224 sq. ft. Membrane Set No. 3 was used in this flow configuration.

The Reynolds numbers applicable to each of these configurations are derived and listed, for the normal flow rates specific to each, in Section VIII.

Membrane Specifications

Four sets of membranes were used on the Universal unit. The manufacturer states:

> "...UWC (Universal Water Corporation) tubular modules are lined with membranes prepared from proprietary formulations, specifically pyridine modified CA (cellulose acetate) solutions. They are independently cast by the bob method, wrapped with a nylon backing and inserted into the tubular module and heat-treated in site."
>
> "Performance (membrane) characteristics are controlled through casting solution formulation variations and heat treatment conditions. Standardized membrane performance characteristics range from high flow - low selectivity (rejection) ultra-filtration systems to membranes capable of single pass (at low flux-high selectivity rejections)."
>
> "Compaction characteristics of the cellulose acetate membranes generally yield a slope of 0.008 to 0.015 for the plot log flux (mg/sq. cm - sec) x 10^{-5} vs log time hours.

One of the purposes of this R.O. study was to investigate different membrane characteristics. Sections IX through XIII discussed test results with different membrane formulations (cellulose acetate vs nylon or asymetric aromatic polyamide materials) and different membrane configuration (tubular, spiral wound or hollow fiber) concepts. The four Universal cellulose acetate membrane sets not only contributed useful information to compare these aforementioned characteristics but the formulations were altered so that low product water flux, high solute rejection ("tight) membranes could be compared with the high product water flux, low solute rejection ("loose") membranes. The detailed operational performance for each of the four Universal cellulose acetate membrane sets will be discussed subsequently. Table 75 compares the TDS rejection ratios and product water flux specifications reported by Universal and the performance of similar membranes in this pilot study, using various post-treated secondary effluent feeds. Membrane Set 2, which was the high product water flux-low solute rejection membrane, performed relatively poorly as shown

Table 75. REVERSE OSMOSIS MEMBRANE PERFORMANCE COMPARISON, UNIVERSAL VS. HEMET TESTS

	Universal Tests				Hemet Tests			
Membrane Set No.	Type	Total TDS Rejection	Flux (GFD)	Op. Press. (P.S.I.)	Total TDS Rejection	Flux (GFD)	Op. Press. (P.S.I.)	Weeks On Stream
1	CA-89	0.935	19	-	0.910	15.5	651	22
2 *	CA-P-70	0.725	31	-	0.506	26.4	675	10
3	CA-P-88	0.955	17	-	0.954	14.9	593	14
4	CA-P-90	0.965	16	-	0.964	11.0	599	22

* High product water flux - low solute rejection membrane.

by the substantially lower TDS rejections, and the rapid membrane deterioration (which will also be subsequently discussed). The "loose" membrane concept was rejected for further study in this program.

Chronological Record

The following notes are abstracted from the plant data logs to show the major events and changes in operation made on the Universal unit during the progress of the study.

Week and Day

2	4	Start of data collection. Membrane Set No. 1; flow pattern "p". Operated using reactor-clarified, sand and activated carbon filtered, pH adjusted secondary effluent.
3	1	Unit out of service, severe vibration.
3	6	Unit back in service.
4	4	Started in-plant chlorination of reverse osmosis feed.
7	4	Started recycling part of brine flow.
7	5	Feed treatment sequence modified to reactor-clarification, sand and carbon filtration, followed by D.E. filtration, chlorination and pH adjustment.
11	5	Stopped recycling part of brine flow.
16 to 19	4 3	Erratic operation - unit vibrating, rupturing membranes, etc.
22	4	No pH adjustment to feed.
23	3	Resumed pH adjustment.
23	5	Installed "loose" membrane Set No. 2; flow pattern "q".
28	4	Decreased feed flow rate by about 40% (to 8 gpm) to improve product water recovery.
29	5	Changed to flow pattern "r".
30	7	Feed treatment sequence modified to include reactor-clarification, sand and carbon filtration with chlorination and pH adjustment.
32	3	Installed membrane Set No. 3; flow pattern "s".
33	7	Removed reactor-clarification from feed treatment sequence.
41	4	Resumed reactor-clarification of feed.
46	3	Unit off; awaiting new modules.
48	5	Installed membrane set No. 4; returned to flow pattern "p". Dropped activated carbon from feed treatment sequence.
57	7	Discontinued reactor-clarification of feed. New sequence: sand filtration, chlorination and pH adjustment.
64	4	Discontinued sand filtration of feed.
69	7	Stopped testing program.

Data Groupings

The Universal unit, like others involved in this study, experienced a range of feed qualities, membrane types, flow configurations, etc. The collected process data should reflect the effects of these conditions and are grouped therefore according to process conditions. Their respective time periods are shown in Table 78. The primary time groupings such as weeks 2-3, 4-6, 7-11 are representative of relative uniform operating conditions. Some of the primary groups, however, were combined in order to give a general idea of the performances by the different membrane sets. Such data groupings have narrow limits of value.

Mechanical and Operational Problems

The Universal reverse osmosis unit had very few mechanical and design problems. Initial difficulties were of relatively short duration. The unit vibrated so badly during the first months of operation that it was shut down on many occasions. The vibration is believed to have been caused by a misaligned feed pump drive shaft.

Although no serious problems arose because of the Universal membranes' susceptibility to internal collapse, caution was exercised at all times to avoid forming a partial vacuum within the tubes. Other operational or membrane problems were minimal. From week 2 to week 46 and from week 48 to week 69, there were 10,896 available operating hours. The unit operated for 94.31% of this time. Tables 76 and 77 both are indicators of the Universal membrane sets.

Table 76. OUT-OF-SERVICE RECORD, UNIVERSAL UNIT

	Hours	%
Mechanical problems	240	2.20
Membrane cleaning	74	0.68
Membrane failures	194	1.78
Alterations, additions	5	0.05
Pretreatment feed problems	107	0.98
Total down time	620	5.69

Table 77. STUDY LIFE SPANS, UNIVERSAL MEMBRANE SETS

Membrane Set	Weekly Group	Weeks On Stream	No. Of Replacements
1	2-22	21	14
2	23-32	10	0
3	33-46	14	0
4	48-69	22	5
		Total	19

Table 78. PROCESS INFORMATION, UNIVERSAL UNIT

Week Nos.	Post Treatment	Membrane Set	Flow Pattern	Special Conditions
2-3	A, B, C, F	1	p	-
4-6	A, B, C, E, F	1	p	-
7-11	A, B, C, D, E, F	1	p	Reject Recirculation
12-21	A, B, C, D, E, F	1	p	Severe Vibration
22	A, B, C, D, E, F	1	p	No pH Adjustment
2-22	Various	1	p	(Consolidated groupings, see above)
7-22	A, B, C, D, E, F	1	p	-
23-27	A, B, C, D, E, F	2	q	-
28-29	A, B, C, D, E, F	2	q	Lowered GPM Feed
23-29	A, B, C, D, E, F	2	q	-
30	A, B, C, D, E, F	2	r	-
23-30	A, B, C, D, E, F	2	q, r	-
30-32	Various	2	r	-
23-32	Various	2	q, r	-
33	A, B, C, E, F	3	s	-
34-41	B, C, E, F	3	s	-
42-46	A, B, C, E, F	3	s	-
33-46	Various	3	s	-
48-57	A, B, E, F	4	p	-
58-63	B, E, F	4	p	-
64-69	E, F	4	p	-
48-69	Various	4	p	-

Post Secondary Treatment Legend

A = Reactor-Clarification
B = Sand Filtration
C = Activated Carbon Filtration
D = D. E. Filtration
E = Pre-R.O. Unit Chlorination
F = pH Control

Water Permeability Data

Table 79 shows the water permeability data ratios. The essential information includes the test parameters (feed treatment conditions, membrane set, flow pattern), average A value, the log A-time slope of the A values and the GFD (gal./sq. ft. day). Although it was "tighter", membrane set number 4 also required cleansing about every 100 hours. This is mainly attributed to the poorer feed quality used toward the end of the study.

Having discussed R.O. data consistency and permeability generally in Section V, it is now desirable to evaluate the specific reliability of the Universal water permeability data. If we assume that correlation coefficients greater than 0.7 represent good consistency and coefficients in the range of 0.5 to 0.7 are marginal but acceptable, then the data for weeks 4-6 and 7-11 should be questioned. Note that the slope is positive in the 4 to 6 week grouping. This was caused primarily by a sudden rise in A values (1.7 to 2.1 x 10^{-5}) about halfway through the period. Experience has shown, and this is probably no exception, that unprecedented rises in A values are usually caused by undetected leaks in the membrane. Two leaking tubes were removed from service shortly after the time grouping, leaving the data substantially weighted. Over-lap of the "leaking membrane" data into the next time grouping (7-11) was responsible for a low correlation coeffient there.

Data for the 31-32 weekly time grouping may also be in error. Applying standard deviation, there is an 80% chance that the true slope was anywhere between -0.0139 and +0.0033. However, some reliability can be placed in the -0.0053 value, as operating conditions were normal for the period.

A low correlation coefficient was also obtained for week 33 to 46 (membrane set 3, flow pattern "s"). The absence of the reactor-clarifier from the post secondary treatment sequence (weeks 34-41) probably accounts for this result. The log A-log time slopes and their standard deviations appear to be normal in the sub-groups within the 33 to 46 week period.

The data for the 64 to 69 weekly period is both aberrant and erratic. The former condition is the result of using low quality feed, which was chlorinated, pH adjusted secondary effluent. The erratic nature of the data stems from the numerous membrane rejuvenations during the period.

Water Recovery and Total Rejection Ratios

Tables 80, 81 and 82 give the feed, product and brine water qualities respectively. It was from these values that the water recovery and rejection ratios were computed. The water recovery ratios of Table 83 are data averages for the indicated time periods at ambient temperature. Confidence levels for these were calculated for each membrane service period in Table 84.

Table 79. WATER PERMEABILITY DATA, UNIVERSAL UNIT

Week Nos.	No. Data Sets	Avg. A x 10^5	Log A - Log T Slope	Std. Dev. Slope	Correl. Coeff.	Avg. G.F.D.	Avg. Eff. Op. Press. (P.S.I.)
2-3	5	2.013	-0.0397	0.0120	.886	14.52	669
4-6	15	1.881	+0.0254	0.0179	.366	13.57	537
7-11	20	2.375	-0.0079	0.0039	.433	17.14	506
12-21	41	2.134	-0.0399	0.0079	.630	15.40	536
22	4	2.378	+-.0480	0.0283	.768	17.16	525
2-22	85	2.150	+0.0197	0.0104	.204	15.51	533
7-22	65	2.223	-0.0359	0.0079	.496	16.04	523
23-27	24	4.992	-0.1191	0.0187	.805	36.02	490
28-29	6	2.462	-0.0252	0.0215	.505	17.76	610
23-29	30	4.486	-0.1780	0.0305	.740	32.37	513
30	7	1.890	-0.0174	0.0037	.905	13.64	574
23-30	37	3.995	-0.2407	0.0363	.746	28.82	530
31-32	7	1.839	-0.0053	0.0060	.364	13.27	571
30-32	14	1.865	-0.0168	0.0036	.807	13.46	580
23-32	44	3.652	-0.2771	0.0347	.776	26.35	539
33	8	2.179	+0.0160	0.0174	.352	15.72	517
34-41	35	20.030	-0.0015	0.0051	.050	14.65	514
42-46	23	2.082	-0.0062	0.0057	.230	15.02	534
33-46	66	2.066	-0.0051	0.0049	.130	14.91	520
48-57	47	1.691	-0.0551	0.0118	.571	12.20	516
58-63	30	1.391	-0.0665	0.0199	.533	10.04	537
64-69	27	1.360	-0.0124	0.0155	.158	9.81	545
48-69	104	1.519	-0.0923	0.0111	.637	10.96	544

Table 80. pH ADJUSTED FEED WATER QUALITY, UNIVERSAL

				mg/l except spec. cond. as micromhos							
WEEK	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARD-NESS	ORTHO-P	ALKA-LINITY	CALCIUM	NO_3-N	SO_4
2-3	-	1119.6	-	28.96	-	-	-	-	-	-	-
4-6	786.7	1256.5	-	22.53	23.53	-	-	-	-	-	-
7-11	2349.0	1222.6	-	12.30	-	-	-	-	-	-	-
12-21	734.5	1309.2	130.54	9.15	8.11	211.91	2.50	46.97	60.57	4.16	364.58
22	720.0	1396.4	115.38	5.80	3.10	208.33	0.86	-	55.74	4.80	149.53
2-22	1166.8	1268.2	212.12	13.61	11.01	210.87	2.17	46.97	59.15	4.25	317.14
7-22	1238.1	1287.8	212.12	9.76	7.39	210.87	2.17	46.97	59.14	-	317.14
23-27	743.0	1229.5	131.47	6.88	4.03	190.55	6.27	57.65	54.10	-	290.85
28-29	710.0	1192.0	-	6.00	4.70	182.92	6.70	85.76	43.01	-	321.21
23-29	733.6	1220.5	131.47	6.63	4.25	188.51	6.41	64.64	50.93	-	290.85
30	740.0	1149.3	-	6.70	3.70	220.08	10.09	-	58.03	-	345.96
23-30	734.4	1211.3	131.47	6.64	4.17	192.40	6.86	64.64	53.16	-	309.43
31-32	707.5	1227.8	-	-	3.80	196.06	6.26	32.14	50.99	-	325.14
30-32	718.3	1201.6	-	6.15	3.76	203.97	7.54	32.14	53.35	-	332.56
23-32	729.0	1214.1	131.47	6.52	4.09	193.41	6.94	58.24	51.71	5.09	313.87
33	775.0	1250.0	-	6.09	5.19	236.36	7.77	-	-	-	333.33
34-41	778.8	1212.8	131.40	10.83	5.76	225.50	14.27	81.45	-	0.60	321.43
42-46	760.0	1203.5	120.69	8.33	-	221.00	7.08	32.33	-	10.00	366.67
33-46	773.8	1203.9	128.68	9.71	5.19	227.00	11.64	65.24	-	3.73	363.75
48-57	785.0	1237.2	149.23	34.0	24.9	236.67	8.00	41.83	65.44	8.24	345.55
58-63	805.0	1242.8	150.00	41.6	-	222.50	7.50	68.05	57.14	5.50	361.66
64-69	811.7	1970.6	137.50	56.9	33.40	222.67	11.00	51.53	69.50	3.93	375.00
48-69	797.7	1435.9	147.9	43.7	28.07	230.00	10.33	52.08	60.75	5.85	340.00

Table 81. PRODUCT WATER QUALITY, UNIVERSAL

mg/l except spec. cond. as micromhos

WEEK NOS.	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARD-NESS	ORTHO-P	TOTAL ALKA-LINITY	CALCIUM	NO_3-N	SO_4
2-3	-	103.0	-	1.100	-	-	-	-	-	-	-
4-6	100.0	86.7	-	1.667	1.600	-	-	-	-	-	-
7-11	122.0	238.4	-	1.440	2.150	-	-	-	-	-	-
12-21	100.6	170.2	31.20	1.070	1.767	29.8	0.210	20.76	5.33	2.25	26.25
22	70.0	155.0	12.00	3.500	0.800	10.00	0.450	-	3.40	3.60	6.00
2-22	104.5	167.4	28.00	1.375	1.718	26.57	0.258	20.76	4.85	2.42	22.20
7-22	105.4	190.6	28.00	1.337	1.744	26.57	0.258	20.76	4.85	2.42	22.20
23-27	168.0	434.4	45.75	2.320	1.225	34.68	0.834	32.40	9.36	1.10	13.67
28-29	512.5	832.0	-	4.300	1.850	135.00	5.000	27.70	28.30	-	159.00
23-29	266.4	548.0	45.75	2.886	1.433	63.34	2.024	31.22	14.77	1.10	50.00
30	530.0	893.0	-	5.400	2.300	160.00	3.400	-	41.20	-	210.00
23-30	299.4	591.1	45.75	3.200	1.557	75.42	2.196	31.22	18.07	1.10	82.00
31-32	605.0	1035.0	-	-	1.950	87.05	3.015	10.80	23.10	-	112.50
30-32	580.0	987.7	-	2.700	2.067	111.37	3.143	10.80	29.13	-	145.00
23-32	360.5	679.9	45.75	2.844	1.644	77.75	2.360	27.14	19.08	1.10	90.71
2-32	-	332.7	35.10	1.831	1.685	58.56	1.659	23.95	15.01	2.27	62.17
33	30.0	60.0	-	1.000	0.700	5.20	0.070	-	-	-	3.00
34-41	40.0	57.0	9.33	1.625	1.014	4.51	0.157	12.95	-	0.33	2.25
42-46	25.0	68.6	7.00	0.500	-	4.42	0.092	10.70	-	2.60	5.50
33-46	35.4	61.4	8.75	1.292	0.867	4.54	0.128	12.20	-	1.09	2.91
48-57	35.5	53.2	3.88	2.480	1.667	2.84	0.024	11.63	0.58	1.66	3.11
58-63	21.7	52.2	4.50	0.333	-	2.67	0.040	12.93	0.40	1.10	2.17
64-69	25.0	67.0	5.50	1.933	0.167	2.72	0.033	12.47	0.41	0.71	1.50
48-69	28.9	56.0	4.29	1.529	0.786	2.76	0.031	12.24	0.48	1.14	2.38
2-69	-	185.4	15.93	1.629	1.306	20.72	0.564	14.95	6.29	1.56	18.82

Table 82. BRINE QUALITY, UNIVERSAL

			mg/l except spec. cond. as micromhos							
WEEK NOS.	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	TOTAL HARD-NESS	ORTHO-P	ALKA-LINITY	CALCIUM	NO_3N	SO_4
2-3	-	1962	-	-	-	-	-	-	-	-
4-6	-	1699	-	-	-	-	-	-	-	-
7-11	-	6035	-	-	-	-	-	-	-	-
12-21	5330	3463	388	123	2200	-	-	600	8.2	2700
22	-	2285	206	10.6	-	-	-	-	6.2	-
2-22	-	3613	343	94.8	2200	-	-	-	7.7	2700
7-22	-	4182	343	94.8	2200	-	-	-	7.7	2700
23-27	1115	2245	189	5.3	359	33.6	34.0	95.0	3.9	-
28-29	958	1738	-	4.0	219	17.5	-	61.7	0.8	-
23-29	-	-	-	-	-	-	-	-	-	-
30	885	1599	-	5.4	-	9.7	54.0	63.0	0.8	-
23-30	979	2041	-	4.6	275	43.9	50.7	69.4	1.9	-
31-32	1155	1504	114	15.3	309	10.5	34.5	83.0	1.6	-
30-32	993	1551	114	12.0	309	10.1	34.5	76.3	1.2	-
23-32	1008	1955	171	7.2	289	38.8	44.2	73.3	1.8	-
33	1275	2263	-	17.2	387	12.0	-	-	1.2	-
34-41	1174	1932	207	13.3	352	22.5	78.3	-	2.7	-
42-46	1243	1721	532	11.8	365	11.3	52.3	-	-	-
33-46	1201	1898	288	13.4	365	18.2	69.6	-	4.3	-
48-57	1458	2389	254	58.6	446	16.1	61.2	122	14.0	739
58-63	1365	2181	222	68.0	404	23.6	80.7	119	7.8	593
64-69	1258	2007	229	71.8	390	19.8	88.8	-	7.0	-
48-69	1371	2232	263	66.9	419	19.1	74.1	121	9.6	704

Table 83. RECOVERY AND TOTAL REJECTION RATIOS, UNIVERSAL

WEEK NOS.	WATER RECOVERY RATIO	T.D.S.	SPEC. COND.	CHLORIDE	TOTAL C.O.D.	DISS. C.O.D.	TOTAL HARD-NESS	ORTHO-P	TOTAL ALKA-LINITY	CALCIUM	NO_3-N	SULFATE
2-3	.489	-	.908	-	.962	-	-	-	-	-	-	-
4-6	.320	.873	.931	-	.926	.932	-	-	-	-	-	-
7-11	.799	.948	.805	-	.883	-	-	-	-	-	-	-
12-21	.643	.863	.870	.761	.883	.782	.859	.916	.558	.912	.458	.928
22	.396	.903	.889	.896	.397	.742	.952	.477	-	.939	.250	.957
2-22	.608	.910	.868	.782	.899	.844	.874	.881	.558	.918	.430	.930
7-22	.676	.915	.852	.782	.863	.764	.874	.881	.558	.918	.430	.930
23-27	.430	.774	.647	.662	.663	.696	.818	.867	.438	.827	-	.953
28-29	.425	.278	.302	-	.283	.606	.262	.254	.677	.31	-	.505
23-29	.428	.637	.551	.662	.565	.663	.664	.684	.517	.710	-	.834
30	.388	.284	.223	-	.194	.378	.273	.663	-	.290	-	.393
23-30	.423	.592	.512	.662	.518	.627	.608	.680	.517	.652	-	.735
31-32	.416	.145	.157	-	-	.487	.556	.518	.664	.547	-	.654
30-32	.407	.193	.178	-	.561	.451	.454	.583	.664	.454	-	.564
23-32	.422	.506	.440	.662	.564	.598	.598	.650	.534	.631	.784	.711
33	.500	.961	.952	-	.836	.865	.978	.991	-	-	-	.991
34-41	.363	.949	.953	.929	.850	.824	.980	.989	.841	-	.437	.993
42-46	.341	.967	.943	.942	.940	-	.980	.987	.669	-	.740	.985
33-46	.365	.954	.949	.932	.867	.833	.980	.989	.813	-	.708	.992
48-57	.491	.955	.957	.974	.927	.933	.988	.997	.722	.991	.798	.991
58-63	.424	.973	.958	.970	.992	-	.988	.997	.810	.993	.800	.994
64-69	.366	.969	.966	.960	.966	.995	.988	.997	.758	.994	.819	.996
48-69	.439	.964	.961	.971	.965	.972	.988	.997	.765	.992	.805	.993

Table 84. UNIVERSAL WATER RECOVERY DATA

Weekly Period	Membrane Set	Average Recovery Ratio	Standard Deviation	No. Of Data Pts.	80% Confidence Level
2-22	1	.608	.186	21	.36 - .85
23-32	2	.422	.053	10	.35 - .50
33-46	3	.365	.045	14	.30 - .42
48-69	4	.439	.079	22	.34 - .54

The water recovery data were examined and it was found that 80% of the values for the weekly period 2-22 fell within the limits of 0.34 and 0.88, thus validating the statistically derived limits of 0.36 to 0.85. The median value was 0.56. There were two approximate modes occurring at about 0.36 and 0.60. This would indicate a two-peaked distribution curve with the first centering at about week 6 and the second at about week 11.

It will be recalled that a portion of the brine flow was recycled as unit feed from week 7 to week 11. This correlates to erratic material balance ratios obtained during this same period.

Recirculation was undertaken for two reasons. First, it was hoped that the overall water recovery ratio might be improved, even at the cost of decreasing the A value; second, it was considered desirable to simulate the conditions of using modules in a long series. The first objective was realized, improving the recovery ratio from about 0.4 to 0.8. Whether the second was attained is questionable.

There are three levels of interest for the total rejection ratios:

1. The ratio for a particular ingredient, such as T.D.S., for the entire test period of a given membrane set;
2. The variations observed within a particular membrane group as related to the various types of pretreatment applied to the feed;
3. The ratio of a particular total rejection to the equivalent ratios for other impurities.

The total T.D.S. rejection ratios for membrane set 2 (the low solute rejection, high flux type) were lower than Universal had anticipated. The low ratios were particularly evident in weekly periods 28-29, 30 and 31-32 during which the feed pressure was increased from about 500 to 600/650 psi in an attempt to improve the product water flux. The manufacturer diagnosed the trouble as premature high-rate compaction accompanied by multiple surface cracking in the thinner film. Under these circumstances, the aforementioned "collapsing" would have occurred even under minimal pressures such as 200 to 250 psi. It is of some interest and to the credit of the Universal membrane that few changes occurred in the total rejection ratios as reactor-clarification, sand and activated carbon filtration were removed from the feed treatment sequence.

Average Rejection and Material Balance Ratios

Table 85 shows the calculated average rejection ratios for the major chemical constituents and the corresponding material balance agreement ratios. Deviations for the ratios are given in Appendix A-1.

The significance of the Material Balance Agreement Ratio (E) and its use in detecting data inconsistencies has been discussed in Section V.

Total C.O.D. and nitrate-nitrogen material balance agreement ratios varied greatly between week 22 and week 46. Original record sheets suggest that the brine samples and/or analyses were in error.

Uniform ratios among the other constituents, nearly discounts leaking membranes as a cause for nitrate nitrogen and C.O.D. inconsistencies. The fact that no membrane changes were necessary during this period also supports this view.

Membrane Set No. 2, in service during weeks 23 to 32, showed high constituent levels in the product water and low rejection ratios. Since the set was designated as a loose, high flux type of membrane, this result was not unexpected. The 2-32 and 2-69 weekly groupings also reflect the lower rejection conditions of weeks 23-32 but to a lesser degree, and this should be remembered when analyzing the performance characteristics of the Universal installation.

Membrane Fouling and Cleansing

The tubular Universal R.O. unit operated significantly longer between membrane cleansings than the other R.O. units. Several reasons could account for this operational result: (1) the product water recovery ratios were generally low (Table 82). This lower product water recovery ratio is partly due to reduced surface area for membrane sets 2 through 4. Also Table 75 shows that the product water fluxes in the Hemet tests were substantially less than the product water flux specifications furnished by Universal. Thus the brine flow rates were higher and probably well into the turbulent Reynolds Number region (above 5,000 Reynolds Number). (2) Four different membrane sets were used. These rather frequent membrane replacements helped reduce permanent membrane fouling and therefore reduced the need for more frequent membrane rejuvenations. There may be some operational advantage to the practice of replacing membranes at regular intervals. However, more operational experience is needed to determine whether there is a corresponding cost advantage to replacing membranes at regular intervals.

The Universal unit's membranes were flushed forty-nine times with a Biz solution, twelve times with a low pH water mix and once with EDTA. The average per cent flux recovery for each membrane set and type of flush is shown in Table 86.

Table 85. AVERAGE REJECTION AND MATERIAL BALANCE RATIOS, UNIVERSAL UNIT

Week Nos.	Average Rejection Ratios						Material Balance Agreement Ratios					
	T.D.S.	Spec. Cond.	Total C.O.D.	Total Hard-Ness	Ortho-P	NO_3-N	T.D.S.	Spec. Cond.	Total C.O.D.	Total Hard-Ness	Ortho-P	NO_3-N
2-3	-	.939	-	-	-	-	-	1.082	-	-	-	-
4-6	-	.943	-	-	-	-	-	1.004	-	-	-	-
7-11	.942	.933	-	-	-	-	.354	.917	-	-	-	-
12-21	.954	.932	.973	-	-	.570	.881	1.007	4.164	-	-	.865
22	-	.922	.817	-	-	.374	-	1.143	3.621	-	-	1.140
2-22	.946	.934	.942	-	-	.505	.530	.999	4.055	-	-	.957
7-22	.946	.932	.942	-	-	.505	.530	.987	4.055	-	-	.957
23-27	.775	.718	.512	.754	.868	-	1.039	1.057	.653	1.144	.909	-
28-29	.355	.370	.144	.309	.306	-	1.028	1.008	.694	1.009	.995	-
23-29	.565	.618	.389	.605	.681	-	1.033	1.043	..667	1.099	.938	-
30	.342	.271	.107	-	.644	-	.997	.994	.806	-	.676	-
23-30	.521	.575	.349	.605	.675	-	1.026	1.037	.686	1.099	.900	-
31-32	.202	.202	-	.596	.598	-	1.028	1.000	-	1.113	1.051	-
30-32	.248	.225	.554	.596	.613	-	1.018	.998	1.674	1.113	.926	-
23-32	.430	.500	.430	.601	.658	-	1.027	1.030	.918	1.104	.934	-
33	.971	.963	.914	.983	.993	-	.842	.828	1.492	.824	.754	-
34-41	.959	.962	.850	.984	.991	.772	.964	.987	1.122	.932	1.043	2.893
42-46	.974	.953	.922	.985	.990	.752	1.006	.963	.966	1.064	1.044	.838
33-46	.964	.959	.873	.934	.991	.765	.964	.967	1.128	.996	1.019	2.208
48-57	.971	.970	.949	.992	.998	.868	1.033	.950	.902	1.038	1.006	1.016
58-63	.979	.969	.994	.991	.998	.835	.963	.972	.877	1.019	.996	1.029
64-69	.976	.973	.970	.991	.998	.864	.992	.959	.821	1.036	1.060	1.177
48-69	.974	.970	.971	.991	.998	.863	1.004	.959	.864	1.033	1.019	1.105

Table 86. MEMBRANE REJUVENATION RECORD, UNIVERSAL UNIT

Membrane Set:	Biz	Acid Wash	EDTA
No. 1,			
No. Flushes/22 weeks	7	8	0
Avg. % Flux Increase	11.4	1.8	-
No. 2,			
No. Flushes/10 weeks	12	1	1
Avg. % Flux Increase	18.4	0.9	0
No. 3			
No. Flushes/14 weeks	5	0	0
Avg. % Flux Increase	9.2	-	-
No. 4,			
No. Flushes/22 weeks	25	3	0
Avg. % Flux Increase	18.9	25	-
Total No./168 weeks	49	12	1
Avg. % Flux Increase	16.7	1.9	0

A Value - Time Plots

Figures 33 through 36 show the log-log A vs time (hours) plots for membrane sets 1 through 4 respectively.

Figure 33 (membrane set No. 1) shows a slight positive slope principally because low A values were obtained between 166 and 670 hours (weeks 4-6). Table 79 indicates that the A value during these three weeks averaged only 1.9×10^{-5} as compared with prior and later period averages of 2.0 to 2.4×10^{-5}. The plant data shows that the pH acid feed pump was not functioning properly on four separate nights. Thus the membranes may have fouled. "Normal" fluxes were restored following the Biz flush at week 7. Another reason for the increase in A values was the need to replace membrane sets more frequently during the membrane 1 test period (see Table 77). These frequent membrane set changes were prompted by membrane failures, probably the result of excessive vibration in the Universal R.O. unit (discussed earlier). Frequent membrane replacement may help in maintaining less steep log A-log Time slopes.

Figure 34 for membrane set No. 2, a high flux type, shows that there was an abrupt decline in A at about 685 hours (week 28). The manufacturer was consulted and they expressed the opinion that the flux decline was due to the migration of solute ions into the interior of the membrane. They suggested that the No. 2 set be replaced by a tighter type. Shortly before the membrane change at week 36, the flow pattern was changed (1013 hours) from "q" to "r". Although the flux decline was halted, the membrane was irremediably fouled.

Figure 35 shows that membrane set No. 3 was much more suited to the study feed conditions. Even the elimination of the reactor-clarifier from the treatment sequence at 234 hours had little effect in altering the A value.

Figure 36 indicates the performance for membrane set No. 4, which used both sand filtered, chlorinated, pH adjusted secondary effluent and chlorinated, pH adjusted secondary effluent. The non-conformity of flux data on Figure 36 up to about 2000 hours (week 61), is probably the result of membrane fouling and subsequent cleansing operations. At 2419 hours (week 63) the slime-like material mentioned in Section VIII, sub-section "Membrane Fouling and Cleansing", was found in the Universal unit membranes. It is probable that the slime-like material had been accumulating since about 2000 hours (week 61), when it became a major fouling agent and a cause for poor product fluxes.

As post secondary effluent treatment processes (reactor-clarification granular activated carbon filtration, etc.) were removed, the quality of the secondary effluent feed became more critical to the R.O. units performance. Membrane set number 1 was tested on the highest quality post secondary effluent treatment, i.e. reactor-clarification, sand and granular activated carbon filtration, chlorination, and pH adjustment. Removal of the reactor-clarifier did not result in extensive permanent flux decline. Similarly, the removal of granular activated carbon

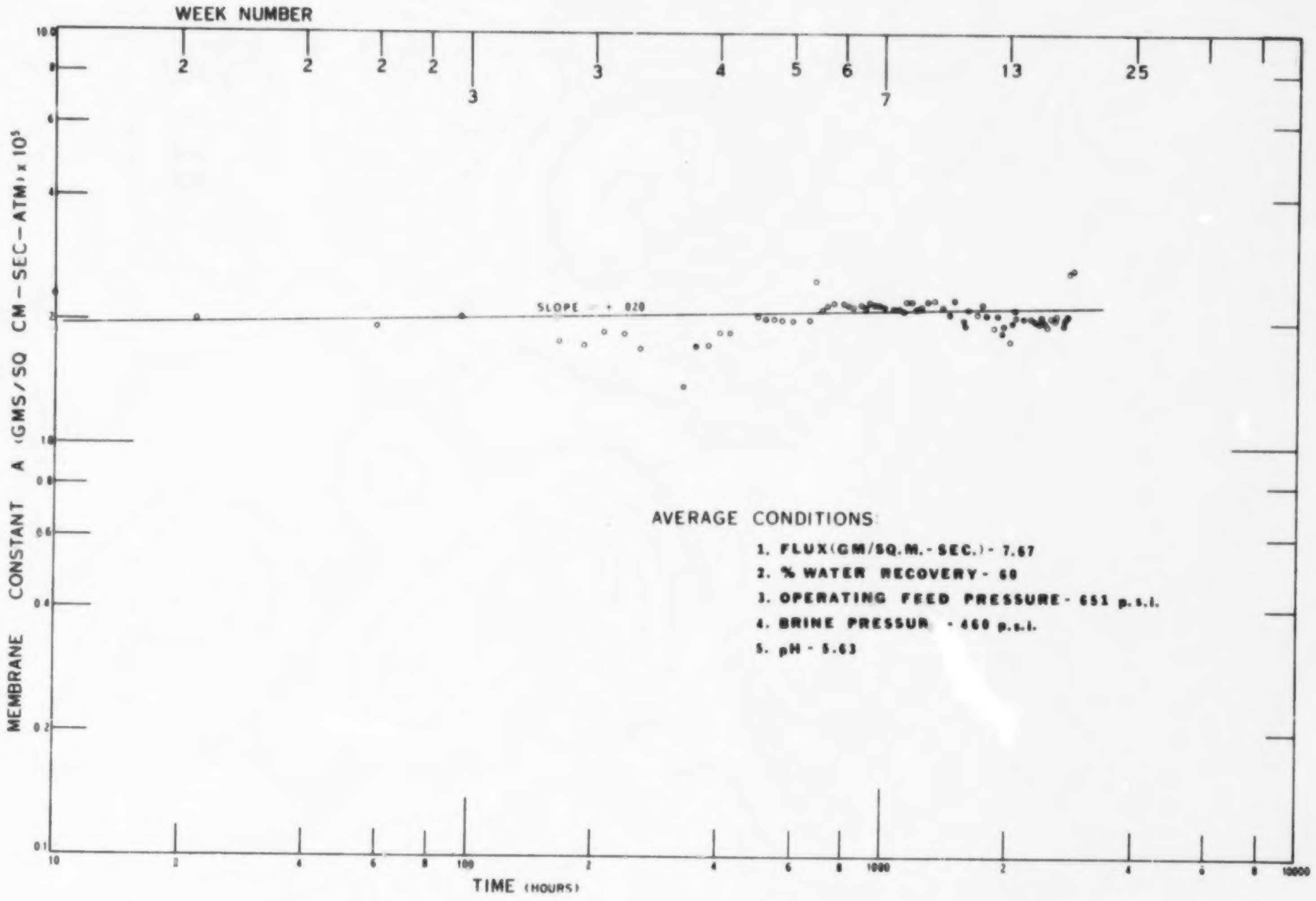


Figure 33. A vs. Time plotted logarithmically, Universal, 3/10/70 - 8/3/70

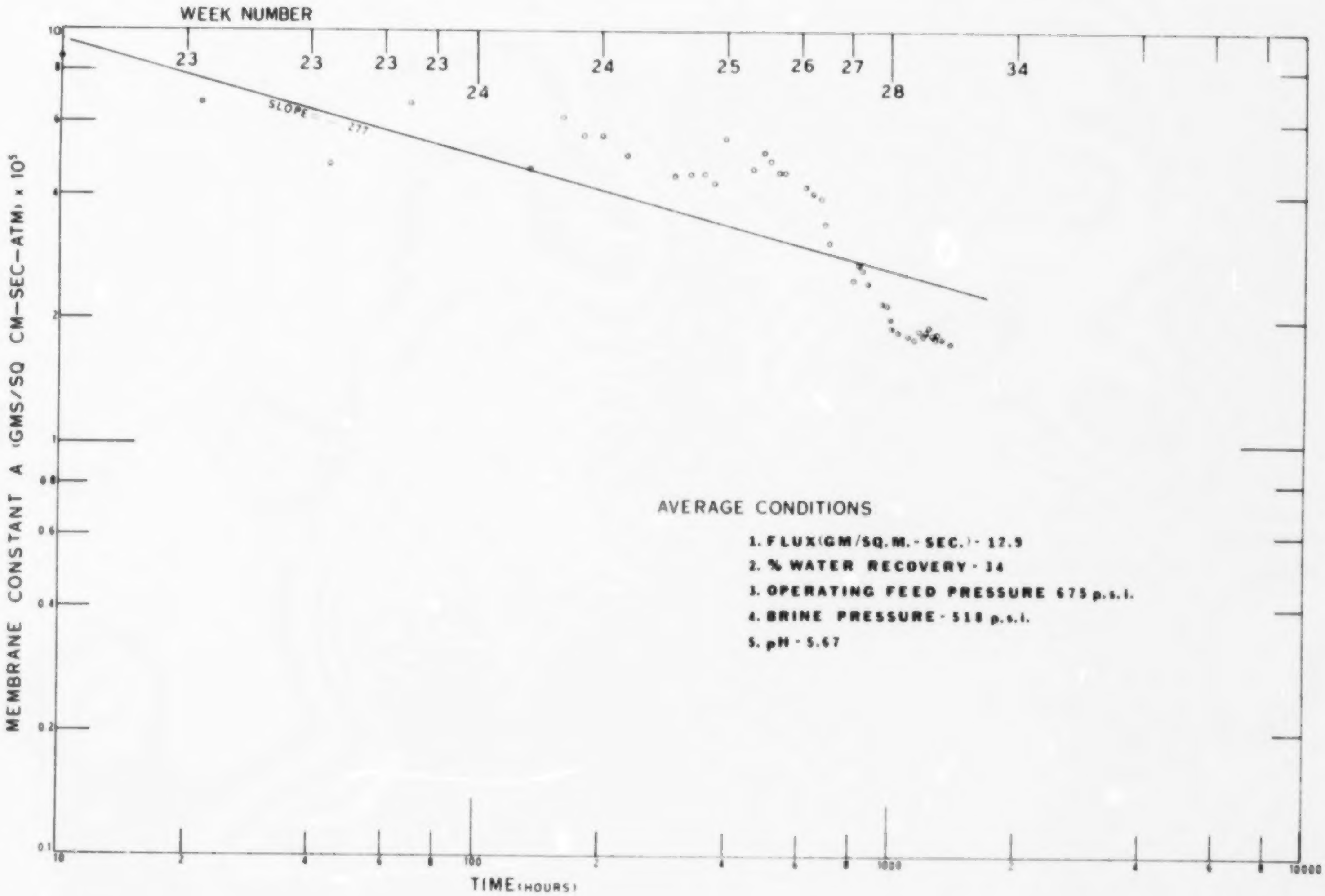


Figure 34. A vs. Time plotted logarithmically, Universal, 8/4/70 - 10/5/70

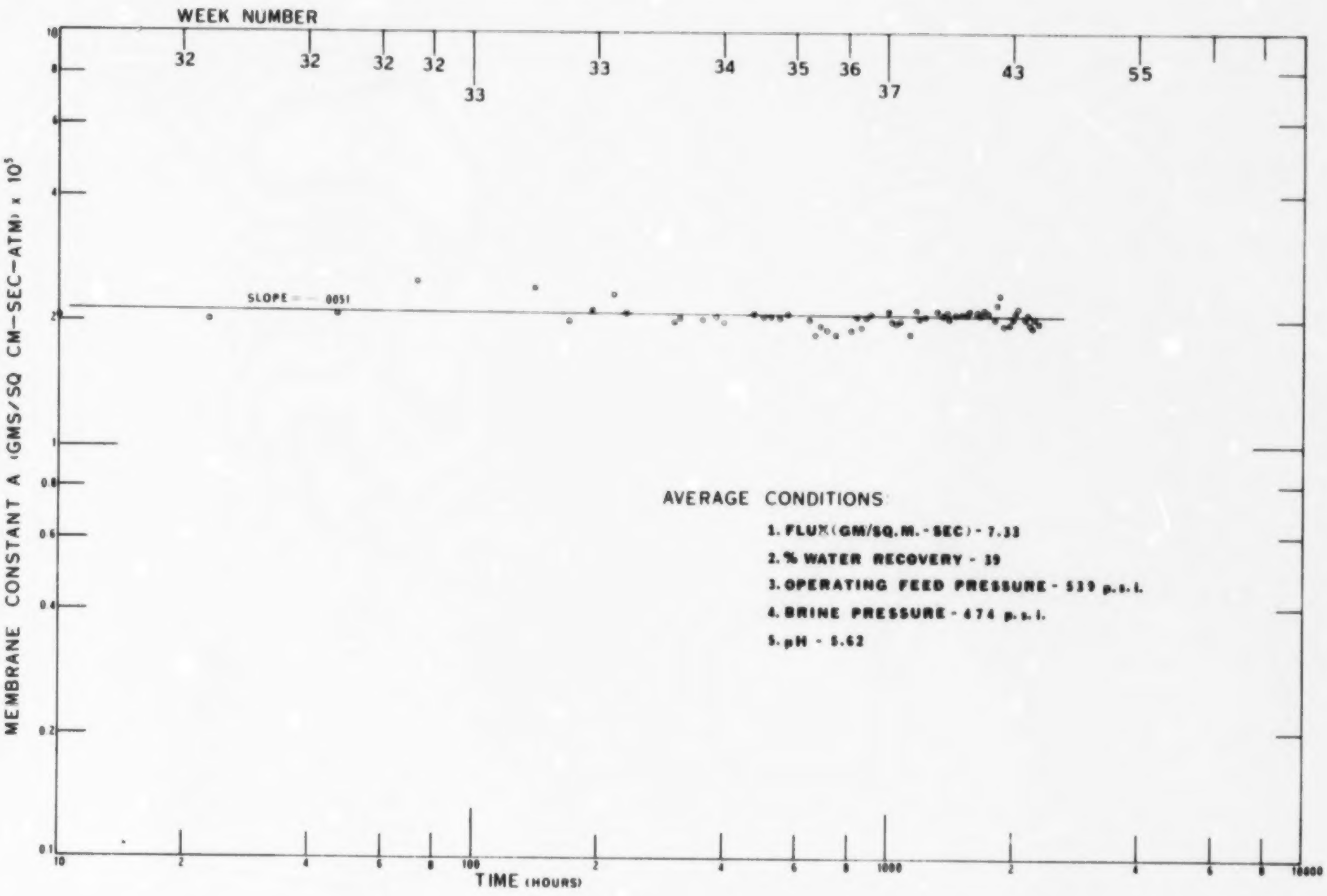


Figure 35. A vs. Time plotted logarithmically, Universal, 10/6/70 - 1/11/71

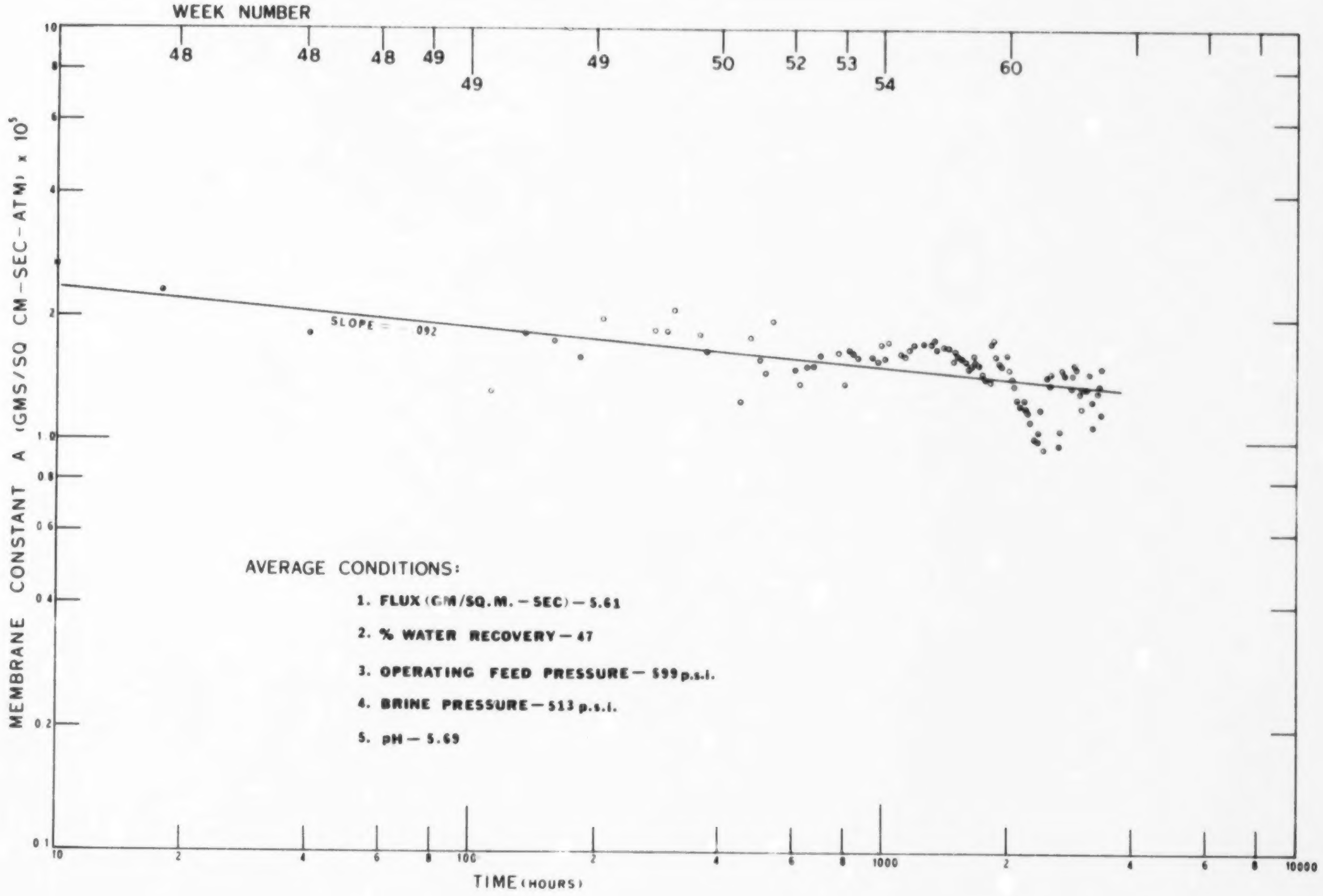


Figure 36. A vs. Time plotted logarithmically, Universal, 1/27/71 - 6/25/71

filtration did not result in extensive permanent flux decline. It wasn't until both the reactor-clarifier and granular activated carbon post secondary effluent treatments were removed that extensive permanent flux decline occurred (Figure 36) and membrane rejuvenation treatments became less effective in recovering product water fluxes. Both the spiral wound and hollow fiber membrane configurations were affected extensively by the removal of either the reactor-clarifier or granular activated carbon post secondary effluent treatments. These results suggest that the advantage of a tubular design over the more densely packed spiral wound or hollow fiber membrane configurations lies in the tubular configuration's capability of tolerating a poorer quality wastewater.

A major upset occurred in the biological treatment plant between weeks 59 and 60. Consequently, all R.O. units were shut down during this period. Plant records indicate that the condition was not fully rectified in the biological treatment plant following resumption of R.O. studies at week 60. Thus, there is a strong possibility that suspended solids were responsible for depressed fluxes toward the end of the project.

SECTION XV

INTER-UNIT COMPARISONS

Introduction

If a comparison is to be made between the R.O. units used in this study, it should be in general terms. It would be inappropriate to compare the units on a specific point-by-point basis since process scheduling and even financial considerations, existing throughout the project, made it impossible to operate all units under the same exact conditions for more than a few brief periods. Some installations and membrane replacement deliveries were delayed. Membrane failures sometimes occurred at critical periods and in these cases replacement modules had to be installed or, in the case of non-availability, the total membrane area had to be reduced. At times, it was necessary to renew modules on one unit while the other units continued to operate under the same post secondary effluent treatment conditions, but with older, fully compacted or partially fouled membranes.

One of the most important findings of this pilot study, however, was that all unit membranes were subject, in various degrees to "Rapid Membrane Fouling." "Rapid Membrane Fouling " is defined as short term or temporary impairment of membrane water permeability (caused by organic and inorganic deposition) which may be eliminated by chemical or physical rejuvenation processes. The rate of fouling is influenced by three factors: 1) the degree of post secondary effluent treatment, 2) membrane formulation characteristics as determined by casting technique and, 3) the flow characteristics within the unit module. It now appears that the periodic rejuvenation procedure is necessary to all R.O. units with the provision that some require it more frequently or for longer durations. Rejuvenation requirements of the pilot study R.O. units are compared below.

Unit Reliability

Table 87 indicates on a unit basis, the hours needed for cleaning and membrane replacement per 100 available operating hours. The values are derived from the maintenance records found in the specific unit discussion sections and Appendix Section A-3. The maintenance time allotment is probably one of the important parameters of reliability. Other out-of-service causes such as mechanical problems were not included as they could represent conditions not directly involved with water transport across a membrane. Thus, if a pump failed, it was either repaired or replaced. (This example does not suggest that finding suitable pumps for reverse osmosis units is always a simple task, but it does assume that high pressure pump technology is relatively advanced compared to reverse osmosis.)

Table 87 can best be understood by using the following discussion as a guide:

Membrane cleansing - for membrane cleansing, the tubular designs, American Standard and Universal, needed substantially less time than the spiral wound or hollow fiber module designs. This indicates that the tubular design tends to remain free of deposition and/or scale and that buildup is curtailed probably because of better flow distribution characteristics. The Aerojet tubular unit required the fewest hours for cleansing, but it was also the unit with the shortest operating span, next to the Raypak tubular unit. The Aerojet unit operated only 14 weeks out of the 69 week study period because of a high membrane failure rate. It would be expected that any R.O. unit would require very little or no cleaning during the brief initial full post-secondary effluent treatment period.

The denser membrane packing of the spiral wound configuration is more susceptible to particulate fouling and more difficult to clean. It is possible that the present hollow fiber cleansing time is less than that indicated in Table 87. The B-5 modules (replaced later by the newer designed B-9 modules) operated on the best post secondary effluent feed. By the time the B-9 modules were installed, the R.O. feed water quality was reduced because of the removal of post secondary effluent treatment processes. However, the cleansing time was essentially the same for the B-9 modules operating on the poor quality feed water as for the B-5 modules operating on the better quality feed. This suggests that the B-9 module could be subject to less fouling, especially from particulates.

Table 87. MAINTENANCE TIME ALLOTMENT/100 AVAILABLE OPERATING HOURS

R.O. Make and Type	Membrane Cleaning	Membrane Failures	Total Hours
AEROJET, TUBULAR	0.13	11.64	-
AMERICAN STANDARD TUBULAR MODIFIED	0.46	2.36	2.82
DU PONT, HOLLOW FIBER	4.32	0.00	4.32
GULF, SPIRAL WOUND	1.11	0.00	1.11
UNIVERSAL, TUBULAR	0.68	1.78	2.46

Another factor to consider in the hollow fiber cleansing experience is the use of cartridge filters on feed water entering the modules. These filters probably slowed the rate of fouling. For this reason cartridge filters are included in the Du Pont reverse osmosis costs of Section XVI.

The second category in Table 87 relates to the hours devoted to membrane failure. Tubular membranes failed more frequently than either the spiral wound or hollow fiber configurations.

The last column lists the total hours devoted to the combined forms of maintenance. The spiral wound design required the fewest total hours for overall servicing. (The Aerojet tubular design was omitted because of the abnormally high membrane failures and early withdrawl from the test study). It is largely because of cleansing that the hollow fiber configuration had the highest total maintenance time.

Water Permeability and Solute Rejections

Tables 88 through 92 compare R.O. data for various post secondary effluent treatment feeds. An outstanding feature is the stability of the rejection ratios regardless of the post secondary effluent treatment. This does not infer that the quality of the product water remains constant. Any solute removed during post secondary effluent treatment results in a lower concentration of solute in the feed and product water; however, the per cent solute removal across the membrane is fairly constant regardless of the feed water solute concentrations.

Table 93 is a summary tabulation that can be used to determine the performance differences between module configurations. The average performance for each membrane configuration was calculated from Tables 88 through 92 for the various R.O. feed waters. The Du Pont B-9 module represents the hollow fiber module concept. From the data in Table 93, it appears that the tubular R.O. concept is less subject to "rapid" and "permanent" membrane fouling than either the hollow fiber or spiral wound configurations, especially in the presence of poor feed conditions.

Table 93 also illustrates the advantage of the tubular designs of operating at a low water recovery ratio. Universal and American Standard R.O. units had relatively gentle A value slopes which is probably the result of low water recovery ratios. The effect of the turbulence promoters in the American Standard tubular unit cannot be determined since there was not a control unit without the turbulence promoters. In providing higher Reynolds numbers, the turbulence promoters through slight, but constant shifting (abrasion) on the membrane surface could have been the major cause of membrane failure and some inconsistent data.

Table 88. OPERATIONAL VARIABLES AND VALUES

FEED TREATMENT: REACTOR-CLARIFICATION, SAND, AND ACTIVATED CARBON FILTRATION (W/CHLORINATION AND pH ADJUSTMENT)

Unit	Weekly Period	Membrane Set	Average Feed P.S.I.	Water Recovery Rate	TDS Total Rejection Rate	A vs T Slope
Aerojet General	7-12	1	565	.424	.744	+.0545
American Standard	19-28	1	605	.805	.785	+.0232
	41-46	1	635	.689	.818	-.0004
Du Pont	24-33	1	650	.770	.594	+.0026
	42-48	2	410	.673	.886	-.0179
Gulf	8-23	1	600	.648	.935	-.0429
	42-46	1	605	.565	.889	-.0006
Universal	2-22	1	645	.608	.910	+.0197
	23-32	2	575	.422	.506	-.2771
	42-46	3	605	.341	.967	-.0062

Table 89. OPERATIONAL VARIABLES AND VALUES

FEED TREATMENT: REACTOR-CLARIFICATION PLUS SAND FILTRATION (W/CHLORINATION AND pH ADJUSTMENT)

Unit	Weekly Period	Membrane Set	Average Feed P.S.I.	Water Recovery Rate	TDS Total Rejection Rate	A vs T Slope
Du Pont	49-53	2	410	.565	.865	-.0060
	55-57	3	415	.566	.891	-.0875
Gulf	47-48	1	620	.482	.890	-.0271
	49-57	2	560	.586	.929	-.1941
Universal	48-57	4	600	.491	.955	-.0551

Table 90. OPERATIONAL VARIABLES AND VALUES

FEED TREATMENT: SAND AND ACTIVATED CARBON FILTRATION (W/CHLORINATION AND pH ADJUSTMENT)

Unit	Weekly Period	Membrane Set	Average Feed P.S.I.	Water Recovery Rate	TDS Total Rejection Rate	A vs T Slope
Aerojet General	35-37	2	555	.556	.862	-.0422
American Standard	38-40	1	630	.756	.811	-.0099
Du Pont	34-37	1	660	.741	.652	-.0069
	38-41	2	415	.684	.933	-.0459
Gulf	34-41	1	600	.623	.911	-.0442
Universal	34-41	3	590	.363	.949	-.0015

Table 91. OPERATIONAL VARIABLES AND VALUES

FEED: SAND FILTER, CHLORINATED, pH ADJUSTED SECONDARY EFFLUENT

Unit	Weekly Period	Membrane Set	Average Feed P.S.I.	Water Recovery Rate	TDS Total Rejection Rate	A vs T Slope
American Standard	61-63	2	635	.724	.898	-.1034
Du Pont	58-63	3	405	.515	.843	-.0780
Gulf	58-63	2	610	.402	.922	-.1095
Universal	58-63	4	590	.424	.973	-.0665

Table 92. OPERATIONAL VARIABLES AND VALUES

FEED: CHLORINATED, pH ADJUSTED SECONDARY EFFLUENT

Unit	Weekly Period	Membrane Set	Average Feed P.S.I.	Water Recovery Rate	TDS Total Rejection Rate	A vs T Slope
American Standard	64-69	2	635	.527	.930	-.0669
Du Pont	64-69	3	420	.351	.766	-.0270
Gulf	66-69	2	600	.290	.913	-.0702
Universal	64-69	4	600	.366	.969	-.0124

Table 93. COMPARISON OF MEMBRANE CONFIGURATIONS

(weeks 38-69)

R. O. Unit	Membrane Configuration	Avg. Recovery Ratio	Avg. TDS Total Rejection Ratio	Avg. A vs. Time Slope
American Standard	Tubular	0.652	0.879	-0.049
Du Pont	Hollow Fiber (B-9 Module)	0.579	0.884	-0.139+
Gulf	Spiral Wound	0.486	0.937	-0.200
Universal	Tubular	0.413	0.971	-0.0604

There are compensating factors of non-tubular R.O. unit designs that can offset what appears to be the advantage of the tubular configuration. The hollow fiber and spiral wound designs' advantages could be: (a) lower membrane failure rate, (b) a more compact unit, (c) smaller space allotment, (d) lower overall production costs, and (e) a possible reduction of permanent membrane fouling tendency.

Table 94 shows the average per cent reductions of constituents for the three main membrane configurations and types of membrane material (formulations). The period from week 38 to week 69 was used for this comparison since the Du Pont B-9 modules were used after week 38. The major post-secondary treatment sequences during the period were: (1) sand filtration plus granular activated carbon treatment, (2) chemical clarification followed by sand filtration, (3) sand filtration only, and (4) no treatment at all. Each of the latter treatment sequences received the usual pre-R.O. chlorination and pH adjustment.

The data indicates that the cellulose acetate membranes are more efficient than the polyamide for removing TDS, dissolved C.O.D., total hardness, calcium, ortho phosphate and sulfate. In all constituent categories, the Universal cellulose acetate membranes equaled or surpassed the rejection performance of the polyamide fibers. However, the polyamide fibers were more efficient for rejection of total C.O.D., nitrates and chlorides than the Gulf cellulose acetate membranes.

Product Water and TDS Rejection Ratios

If reverse osmosis is used for ground water recharge purposes, some blending of the product water with treated or untreated secondary effluent is possible. The four reverse osmosis units listed in Table 93 were originally specified to produce 10,000 GPD product water. However, the effects of compaction, concentration polarization and membrane fouling quickly reduced the product water recovery to something less than the nominal 10,000 GPD specification. A mathematical "adjustment" of the membrane area can therefore be made in order that the nominal 10,000 GPD specification be met. The "adjustment" is necessary for making R.O. cost estimates. A second adjustment is also possible for the TDS rejection ability of an R.O. unit (see Table 95). The values in Table 95 are based on the pilot plant data and are valid provided the following assumptions are made:

(a) 90% TDS rejection
(b) the minimum volume of R.O. product water is blended to produce a 500 mg/l TDS water for ground water recharge
(c) the selected product water volume rates are representative of the best possible output by each R.O. unit (usually when first installed).

The data in Table 95 represents the best estimate that could be made for determining capacity discrepancies which may be encountered in reverse osmosis applications. These values can and will probably differ from

Table 94. AVERAGE PER CENT REDUCTIONS OF CONSTITUENTS

Reverse Osmosis Configuration	TDS	Total COD	Diss. COD	Total Hardness	Ca	Ortho-P	NO_3-N	Ammonia-Nitrogen	Cl	SO_4
Du Pont Hollow Fiber B-9 Modules Polyamide Fibers	88	90	90	95	96	93	84	--	91	94
Gulf Spiral Wound Cellulose Acetate	94	88	92	98	99	99	55	96	88	99
Universal Tubular Cellulose Acetate	97	93	96	99	99	99	84	99	97	99

NOTE: Per cent reductions chosen from weeks 38 to 69, to compare these membrane configurations on the same feed water. Data extracted from program data, exemplified in Table 20.

Table 95. MINIMUM VOLUME INCREASE REQUIRED PER UNIT TO MEET SPECIFIC DEMAND - 10,000 gpd @ 90% REJECTION

Unit	Discrepancy Between "Nominal" (10,000 gpd) Production and Observed Production		Additional Product Necessary to Compensate For Discrepancy Between "Ideal" (90%) and Observed TDS Rejection (%)	Overall Volume Increase Needed to Produce a Product Analogous to 10,000 GPD At 90% Rejection (%)
	(GPD)	(%)		
American	-1252	-14	+13	+31
Du Pont	+2360	+19	+27	+ 3
Gulf	-2645	-36	-	+36
Universal	-1288	-15	+ 5	+21

other installations. Evidence shows that a 90% product water recovery and 90% solute rejection could be stretching reverse osmosis performance to an upper limit when operating on a non-recirculation basis. Experience with the nominal 10,000 GPD American Standard tubular unit indicated severe fouling when attempting to achieve 90% product water recovery operating on a once through basis (Section X). The fouling was partially overcome by operating at a lower (near 80%) product water recovery level. Calcium salts, particularly phosphates and sulfates which have low solubilities, probably scaled the membrane surfaces when operating over the 80% product recovery ratio. However, it is also possible that some 10,000 GPD reverse osmosis units do not provide for sufficiently high Reynolds number after 80% product water is recovered. It would be helpful to have information on larger units for each manufacturer to determine cost declarations and operation ease on a magnified scale. The smaller R.O. units were closer in keeping with the objectives and funds available for the study.

Relative Membrane Product Recovery Losses

Table 96 shows how long the unit membrane sets may be expected to operate under various feeds. The life spans were based on the rate of recovery loss per week. Each recovery loss value was determined using two selected original values of recovery. To eliminate errors due to process changes, the two values were never separated by a process change other than one membrane flush. Because both base values were taken in the 3-5 day period after a membrane "Biz" flush the rate of loss as recorded in column A is considered to be the "permanent recovery loss rate" parameter. After establishing the rate of recovery loss, it was relatively simple to determine parameter B which was based solely on Parameter A. The actual contribution of recovery losses to the total operating costs will be discussed in the next section.

Table 96 is most valuable in evaluating relative membrane life and not as indicating actual membrane life. The actual membrane life evaluation should have more constant operating conditions. However, Table 96 relates the effect of various operating conditions to a theoretical estimate of membrane life. For example, the Universal tubular unit shows a relatively short membrane life for the highest quality feed water (horizontal groups 1 and 2). The reason for this is Universal membrane set No. 2 was used during the test interval. The high product water flux-low solute rejection membrane showed very rapid compaction, fouling, and disintegration which resulted in a rapid decrease in product water flux (slope of A vs T - See Figure 34). The effect of changing to the low product water flux-high solute rejection membrane (set 4) resulted in several magnitudes of increase in the membrane life span even with the application of a lower quality feed water.

Table 96 also shows that there was very little permanent loss of production in the Gulf spiral wound configuration until granular activated carbon filtration was removed from the post-secondary effluent treatment sequence. During the episode of no post secondary treatment except

Table 96. ESTIMATE OF MEMBRANE LIFE BASED ON PRODUCT WATER RECOVERY LOSS

Post-Secondary Effluent Treatment Sequence and Unit	Rate of Permanent Product Water Recovery Loss Per Wk. (A)	Membrane Set No.	Theoretical No. Weeks For Membrane Set To Experience 25% Loss of Product Recovery (B)	Theoretical No. of Membrane Sets Which Would Be Necessary To Replace Per Week Using Maximum 25% Permanent Recovery Loss Criterion (C)
A,B,C,D,E,F				
American Standard	-2.38%	1	11.50	0.09
Du Pont	No data on B-9's	-	-	-
Gulf	No change	1	-	0.01
Universal	-1.65%	1 & 2	15.15	0.07
A,B,C,E,F				
American Standard	-0.78%	1	32.89	0.03
Du Pont	-2.4%	2A	10.42	0.10
Gulf	No change	1	-	0.01
Universal	-5.23%	1,2 & 3	4.78	0.21
A,B,E,F				
American Standard	No data	-	-	-
Du Pont	-5.87%	2A	4.26	0.23
Gulf	-2.00%	1 & 2	12.50	0.08
Universal	-0.87%	4	28.74	0.03
B,E,F				
American Standard	No data	-	-	-
Du Pont	-3.95%	2B	6.33	0.16
Gulf	-4.25%	2	5.88	0.17
Universal	-0.35%	4	71.43	0.01
E,F				
American Standard	-5.57%	2	4.49	0.22
Du Pont	-9.57%	2B	2.61	0.38
Gulf	-0.44%	2	56.82	0.02
Universal	-2.34%	4	10.68	0.09
TOTALS (Simple Averages)				
American Standard	-2.90%		8.62	0.12
Du Pont	-4.55%		5.49	0.18
Gulf	-1.34%		18.66	0.05
Universal	-2.09%		11.96	0.08

pre-R.O. unit chlorination and pH adjustment (treatment, E, F on Table 96), the Gulf unit appears to have experienced only slight loss on product water recovery. The value is misleading, however, unless it is realized that the level of recovery at that time was only 29 per cent.

SECTION XVI

REVERSE OSMOSIS COSTS

Introduction

The feasibility of using reverse osmosis to remove constituents from treated or untreated secondary effluents was the primary purpose of this study. The study was planned so that the data might be used to estimate the economics of reverse osmosis in a local ground water recharge program. The many project variables and details made the costs difficult to estimate. Nevertheless, three different cost estimates will be presented: two were prepared by cooperating R.O. manufacturers (Du Pont and Gulf) and one was prepared by the project personnel at Hemet, California, based upon the study data and experience elsewhere.

Feed Treatment Requirements

Two separate, yet related, factors need to be considered in any reverse osmosis application; flux (water permeation) rate and solute removal. The water permeation rate is affected by such variables as membrane characteristics module configuration, impurities present in the feed water, the operating pH level, the amount of feed water chlorination, the designed product water quality, etc., in addition to the more direct variables such as temperature and the R.O. operating pressure.

Solute removal is influenced primarily by membrane formulation characteristics. In most instances a low solute concentration in the feed water to a reverse osmosis unit results in higher water permeation rates, a better quality product water and diminished membrane fouling problems.

A cost trade-off exists between the extent of feed treatment and reverse osmosis unit maintenance. With the higher cost of treating secondary effluent, there is a corresponding decrease in membrane replacement, rejuvenations and fouling tendencies. An improved feed quality is usually accompanied by better product quality, quantity and lower brine volume, all important cost factors.

When treatment of secondary effluent is considered solely from the standpoint of beneficiating the reverse osmosis process, opinions become divided as to what and how much pretreatment is economically justifiable. The spiral wound R.O. manufacturer (Gulf) suggested that only sand filtration, chlorination and pH control are essential post secondary effluent treatments. The hollow fiber manufacturer (Du Pont) advises that granular activated carbon filtration, polyphosphate addition and ten micron cartridge filters should be added to the post secondary effluent treatments. It is unfortunate that no tubular unit manufacturer was prepared to specify a post secondary effluent treatment sequence with a cost estimate.

The data from this study suggests that the untreated secondary effluent quality has little to do with selection of the best secondary effluent treatment sequence. Instead it was determined that a continuously good quality feed with low rate of membrane replacement can be maintained using reactor-clarification with chemical coagulation and sand filtration and provided that Reynolds number is maintained in the 4,500 - 5,500 range or its equivalent.

Reverse Osmosis Cost Factors

As mentioned in Chapter XV membrane life determination was not a primary objective of this pilot study. It is necessary, however, to have at least a "ball park" estimate in order to arrive at any R.O. cost estimate. There are a number of reasons for assuming a two year membrane life: (1) the spiral wound R.O. unit operated successfully for over a year on only two membrane sets using high and low quality feed: (2) it appears that the hollow fiber unit could have matched the spiral wound unit for membrane longevity had B-9 modules been used at the beginning of the study and (3) a municipal water improvement facility applying R.O. to brackish potable water is assuming a two year membrane life under guarantee. The last reason is valid because the initial feed waters at Hemet were of better physical and chemical quality than many brackish municipal supply waters. As a result of a good quality feed, a low fouling tendency and long membrane life can be expected. The lifespans as calculated in Table 96 of Section XV were not used as cost indicators since conditions were so variable. Instead they are most important for comparative analysis.

Table 95, however, was used to establish whether size increases are always necessary to meet the nominal capacity of the R.O. plants. The Du Pont hollow fiber unit fulfilled its obligation by operating within 3% of the nominal capacity. Therefore, it was unnecessary to apply a volume/TDS rejection adjustment to the following "study" cost estimate.

Reverse Osmosis Cost Estimates

(These cost estimates are based on the first quarter of 1972 ENR Index.)

I. Project Estimate:

An estimate was made using the project data for a minimum 0.8 mgd and possible 0.9 MGD product water facility using 1 MGD feed water. For this cost analysis, reactor-clarification plus sand filtration was chosen over sand filtration plus activated carbon filtration as the post secondary treatment sequence. The latter sequence is somewhat more efficient but the former sequence is usually substantially cheaper and still provides a high degree of treatment.

A. Basic Assumptions

1. The secondary effluent reverse osmosis feed water will first be chemically treated in a reactor-clarifier by either alum or ferric chloride, sand filtered, chlorinated and pH adjusted.

   Note: It would be preferable to first install pilot units of Du Pont, Gulf or Universal manufacture and operate them for a period of six to twelve months to determine:
   (a) whether chemical clarification or granular activated carbon treatments are needed continuously in the full scale plant and
   (b) which make of unit should be selected for the second stage expansion.

2. Plant Operations
   a. Operate 24 hours per day, 7 days per week
   b. An estimated 10% down time (including membrane cleansing, replacement, repairs, etc.)
   c. Membrane replacement every 24 months
   d. Feed pressure 400 psi
   e. Complete automation of all repetitive operations with flow and pressure recorders, and controllers, chlorination, pH and conductivity recorders, automatic sampling devices, time sequential valve operators, automatic shut down and diversion facilities, automated sulfuric acid and flushing solution handling and make up systems, alarms, etc.
   f. With the above listed automation, the following plant and laboratory personnel would be required:

Supervisor - 0.2 man years	$	3,000/year
Chemist (1)		10,000/year
Plant Operators (2)		18,000/year
Relief Operator and Chemist (1)		10,000/year
Instrument Man & Mechanic - 0.3 man years		4,000/year
Subtotal - - - - -	$	45,000/year
Assume 20% for overhead		9,000/year
Total Labor Costs	$	54,000/year

g. All post secondary effluent treatment and reverse osmosis equipment will be located out-of-doors on well drained concrete pads around a paved heavy equipment access road. Included in the complex will be a centrally located 200 sq. ft. roofed and air conditioned building to serve as a combined operators record and instrument room. (Based on a estimated rating of 2,000 gpd per sq. ft. the paved equipment area, exclusive of the operators room and access road, will be about 6,000 sq. ft.)

h. The existing reverse osmosis building on the site will house the warehouse, instrument repair room and shop, the conference room and plant foreman's office, laboratory, washroom, and lunch room.

i. A Pelton wheel driven pump will be provided on the brine stream to recover about 10% of the reverse osmosis unit power. (Note: Although the pay-off on an 800 K gpd rate is only about 10% per year, it is included in this estimate because power recovery will be increasingly desirable should the projected plant be enlarged or operated at lower recovery rates.)

j. No charges are included in this estimate for the following:
   (1) The existing reverse osmosis building
   (2) Secondary effluent delivery system
   (3) Waste brine disposal
   (4) Land Cost (or rental)

Comments: Many of the items listed under (A-2) are inadequately defined at this time. The major cost items (reverse osmosis unit costs, tested membrane replacement time intervals - and costs, labor requirements, etc.) are so affected by unestablished design details (examples - trade off costs between automation and labor costs), quantity discounts, development of improved membranes, etc., that they cannot be estimated at this time. Thus the following cost estimate is a rough approximation using information derived from the EMWD pilot plant studies:

B. Capital Costs

		Cost
1.	Reactor-clarifier and clearwell (overflow rate 0.5 gpm/sq. ft.)	$100,000
2.	Sand filters	30,000
3.	Pumps and Piping	50,000
4.	Secondary Effluent Treatment Setup	5,000
5.	Reverse Osmosis and Field Setup	6,500

6.	Site Preparation	2,500
7.	Paving and Drainage	2,000
8.	Utilities	23,000
9.	Instrumentation other than R.O.	50,000
10.	Power Regeneration	15,000
11.	Chemical Handling	50,000
12.	pH Control	15,000
13.	Chlorination	10,000
14.	Remodeling existing building	5,000
15.	Reverse Osmosis unit	500,000
16.	Product water storage (100,000 gal.)	12,000
17.	Erection and Assembly	32,000
	(1) Sub-Total - - - -	$908,000
	Engineering (approximately 7.65%, ASCE Man. and Reports on Engineering Curve A, 1971)	70,000
	(2) Sub-Total - - - -	$978.000
C.	Other Expenses	
1.	Indirect Field Labor	5,000
2.	Home Office Cost	2,000
3.	Start up Costs	20,000
4.	Contingencies - including working capital, interest during construction, 5% of sub-total (2)	49,000
		$1,054,000
	Less: First Set Membranes (Expensed)	150,000
	Total Capital Costs	$ 904,000

Amortization:
20 years @ 6% - yearly cost
Factor is 0.0872 $ 78,828/yr.

Cost per 1,000 gallons product water
based on 0.9 mgd product water: 24.0¢

Comment: If the amortization used is 10 years at 6%, the yearly cost factor is 0.1359 or $122,854/year and 37.4¢/1,000 gallons.

D. Operation and Maintenance Costs

Item	Yearly Cost	Cost/1,000 gal.
1. Labor - (Ind. O'H)	$ 54,000	16.4¢
2. Electric Power	14,800	4.5¢
(after credit for regeneration)		
3. Membrane Replacement	75,000	22.9¢
($150,000 for 2 year membrane life)		
4. Plant Chemicals	27,900	8.5¢
5. Consumable Supplies	6,500	2.0¢
Total	$ 178,200	54.2¢

Grand Total of Costs - - - - - 54.2¢ + 24.0¢ = 78.2¢/1,000 gallons

Comment: If 10 year amortization life is used, total cost is 37.4¢plus 54.2¢ or 91.6¢/1,000 gallon product water.

Notes: a) If the reactor-clarifier were not installed, it is estimated that the capital costs would be reduced to about $804,000 and the total cost to about 75.5¢/1,000 gallons (21.3¢ + 54.2¢/1,000 gallons). However, if activated carbon filters were added to the post secondary effluent sequence (reactor-clarifier, sand filters, pre-R.O. unit chlorination and pH adjustment) the capital cost for R.O. would be increased to $982,000 and the total cost would be 84.9¢/1000 gal. including the cost of media at 4.6¢/1000 gallons.

b) The following assumptions would apply to a plant with a 9 million gallon capacity:

(1) Capital costs would be adjusted by an 0.8 exponent factor,

(2) The $54,000 annual labor cost would be no higher for a 9 MGD plant than the 0.9 MGD plant.

(3) The power, membrane, chemical, and supply costs remain constant per 1000 gallons of product water. The estimated cost for the larger facility would then be 19.2¢ capital cost plus 54.2¢ O&M cost for a total cost of about 73¢/1000 gallons. An estimate for a 10 MGD plant would not apply to the Hemet facility since the present daily flow rate there is less than 4 MGD.

c) The estimated cost for blending secondary effluent with R.O. product water at Hemet is estimated from the TDS in the secondary effluent (Table 3) which averages 716 mg/l and 72 mg/l TDS in the R.O. product water to produce a blended water with 500 mg/l concentration.

Let X = R.O. product water
1-X = Secondary Effluent
Total = 1 unit

$$\begin{aligned} X(72) + (1-X)(716) &= 1\,(500) \\ 72X + 716 - 716X &= 500 \\ 644X &= 216 \\ X &= 0.34 \end{aligned}$$

Thus 34% R.O. product water can be mixed with 66% secondary effluent to produce a blended water at 500 mg/l TDS. Assuming no added cost for the actual blending operation, the R.O. cost portion is 0.34 x 78.2¢/1,000 gallons or 26.6¢ per 1,000 gallons; and 0.9 mgd R.O. product water can be blended with 1.7 mgd secondary effluent to produce 2.6 mgd blended 500 mg/l TDS water for groundwater recharge.

II. Gulf Environmental System Cost Estimate:

The cost estimate for the spiral wound module offered by Gulf Environmental Systems based on this study data and the manufacturer's experience follows:

A. 1,000,000 gallons product water per day from secondary effluent

B. 75¢ recovery, 97% conductivity rejection, at 400 psi

C. Three groups of units, each with an individual feed pump

D. "Adequate" instrumentation

E. 90 to 95% running time

F. Cost of first set of modules included

G. Three year membrane life (replacements chargeable to expense)

H. No power regeneration

I. Automated membrane flushing operations

J. Total labor-operation and maintenance (no chemists) 1000 hours total per year

K. Ten year amortization period

L. No exterior piping

M. Brine disposal not included

The above assumptions gave the following estimates:

1. Capital Cost $450,000

2. Operating Costs

	¢/1,000 gallons
Power	8
Membrane replacement	15
Cleaning chemicals	6
Operating chemicals	6
Operating labor	1.5
Sub-Total	36.5
Amortization	8.2
Total	45.0¢/1,000 gallons

III. E. I. Du Pont de Nemours Cost Estimates

The cost estimate for the hollow fiber module offered by E. I. Du Pont de Nemours based on this study data and the manufacturer's experience follows:

1. 10,000,000 gallons product water per day from secondary sewage

2. 80% recovery, 90-95% rejection at 400 psi
3. Ten 100 unit sets of permeators, each of the ten divided into two 50-unit control blocks
4. Instrumentation
5. Cost of first set of permeators included
6. Monthly replacement of filter cartridges
7. No power regeneration
8. Membrane flushing controls unstated
9. Labor: four operators and one each of the following: analyst, instrument and maintenance man, helper, clerk-typist, supervisor. Total nine employees
10. Amortization -- see below
11. No exterior piping
12. Brine disposal not included

The estimated capital costs follow:

1.	Permeators (1000 - 8 in. diameter)	$200,000
2.	Fiber	1,800,000
3.	Supports and integral piping	100,000
4.	Pumps and motors (five sets)	200,000
5.	Battery limits piping	200,000
6.	Cartridge filters and cleaning equipment	200,000
7.	Electrical	100,000
8.	Instrumentation	100,000
9.	Cl_2, Acid and polyphosphate piping	30,000
	Total direct cost	$2,930,000
10.	Engineering	370,000
	Total reverse osmosis cost	$3,300,000

11.	Pretreatment (including sand and carbon filters)	500,000
	Total capital cost	$3,800,000

The amortization of this equipment would be:

For 20 years at 6%	5¢/1000 gal. product
For 3 years at 6%	18¢/1000 gal. product

OUT-OF-POCKET COSTS

Item	Comments	¢/1000 Gal Product
Power	80% pump efficiency, 1¢/KWH	4.6
Acid	$33.36/ton, 110 ppm	1.9
Calgon	15¢/lb., 10 ppm	1.6
Chlorine	7.6¢/lb., 0.5 ppm	0.03
Detergent	30¢/lb., 1.0 wgt %/month	0.4
EDTA	50¢/lb., 1.0 wgt %/month	0.6
Cartridge filters	Replaced monthly	4.0
Labor & Maintenance	(As above)	2.2
	Sub-Total	15.33¢
Sand filters, including coagulant aids		5.00
Carbon adsorbtion including regeneration		10.00
	Total	30.33¢

The above total cost is:

1. Plant amortization	5¢/1000 gal.
2. Fiber	18¢
3. Out-of-pocket	15¢
4. Pretreatment	15¢
Total	53¢/1000 gal. product

The manufacturer advised that the major cost difference between a ten million gallon per day plant and a 100,000 gallon per day plant would be the amortization charge. For the smaller plant, this would be 19¢/1000 gallons.

A 100,000 GPD plant would cost about $100,000; $20,000 for the fiber and $80,000 for the auxiliaries. This would give costs of:

1.	Amortization	19¢/1000 gal.
2.	Fiber	20¢
3.	Out-of-pocket	15¢
4.	Pretreatment	15¢
	Total	69¢/1000

Summary of Costs

The "Study" cost estimate is substantially higher than either the Gulf or Du Pont estimates. Two items could partially account for the differences; (1) Membrane life was assumed to be 2 years in this study estimate; both Gulf and Du Pont used a 3 year membrane life and (2) the manpower required, differs substantially between the "Study" cost estimate and the Gulf and Du Pont cost estimates. More information is required on larger size R.O. studies over an extended period in order to obtain better information on R.O. costs.

SECTION XVII

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SECTION XVIII

APPENDICES

Page

A - 1 Glossary, Equations and Derivations 188

A - 2 Daily Record of Feed pH's . . . . (Omitted)

A - 3 Membrane Rejuvenation Data. 203

A - 4 Record of Backflushes for Post-Secondary Filters. 213

A - 5 Comments on Nitrate and Phosphate Analyses 218

A - 6 Computer Printout Summary . . . . (Omitted)

NOTE: Because of paper shortage, Appendices A-2 and A-6 have been omitted from this volume. These sections may be obtained from the National Technical Information Service, Springfield, Va. 22151, as PB-239 354

Beginning with page 197 of this volume, a double set of page numbers appear. One set reflects the original page numbers; the bracketed numbers reflect continuous numbering of this shortened volume.

APPENDIX SECTION, A-1

GLOSSARY, EQUATIONS, AND DERIVATIONS

Glossary:

A	Membrane water permeation rate (gm/sq cm-sec-atm)
A_1	Calculated value for A at end of first hour (gm/sq cm-sec-atm)
A_3	Calculated value for A at end of 1000 hours (gm/sq cm-sec-atm)
B	Solute permeability factor (cm/sec)
b	Tangent of log($A \times 10^5$) vs log time (hrs) regression line
C_a	Avg. solute concentration of feed and reject (mg/l)
C_f	Solute concentration of feed (mg/l)
C_p	Solute concentration of product (mg/l)
C_r	Solute concentration of brine (mg/l)
D	Optimum time between membrane flushings (days)
d	Diameter of the membraned tube (in.)
E	Material balance agreement ratio
F_d	Decrease in product flow rate 24 hours (gal./min)
F_f	Net feed flow rate (gal./min)
F_p	Product flow rate - observed (gal./min)
F_{pc}	Product flow rate - corrected to 25° C (gal./min)
F_r	Brine flow rate (gal./min)
f	Same as F_f (used in N_{Re} estimation) (gal./min)
GFD	Gal./sq ft-day, at 500 P_e (gal./sq ft-day)
J_a	Average solute rejection ratio
J_f	Concentration of feed to a post secondary effluent treatment step (mg/l)
J_p	Concentration of discharge from above step (mg/l)

J_{fp}	Post secondary effluent treatment step rejection ratio
J_t	Total solute rejection ratio
M	Total effective membrane area (sq ft)
N_{Re}	Reynolds number (dimensionless)
n	Number of data points in a set
P_e	Net effective operating pressure (psig)
P_f	Feed pressure (psig)
P_o	Osmotic pressure (psig)
P_r	Brine pressure (psig)
p	Same as F_p (used in N_{Re} estimation) (gal./min)
R_c	Product recovery ratio - corrected to 25° C
R_o	Product recovery ratio - observed
r	Sample correlation coefficient
s_b	Standard deviation of b
s_z	Standard deviation of z
T_f	Temperature of feed (°F)
v	Volume rate of the brine flow from a specific section of a reverse osmosis unit (gal./min)
w	Volume rate of the entire reject from a reverse osmosis unit (gal./min)
X,Y	Logarithms of ($A \times 10^5$) and time (hrs) respectively
x,y	Values defined by Equations (24) and (25)
Z	Any variable
**	Exponent indicator

List of Equations

$$A = (0.998\ F_{pc}) / (M\ P_e) \qquad (1)$$

$$A_1 = \text{Antilog} \left[\left(\sum X\right)/n - b\left(\sum Y\right)/n \right] \qquad (2)$$

$$A_3 = \text{Antilog}\ (\text{Log}\ A_1 + 3b) \qquad (3)$$

$$B = 0.0671\ A\ P_e \left[(1 - J_a) / J_a \right] \qquad (4)$$

$$b = \sum xy / \sum x^2 \qquad (5)$$

$$D = -0.0625 \left[1 + (1 + 32G/F_d)^{\frac{1}{2}} \right] \qquad (6)$$

$$E = E_1 = \left[C_p R_o + C_r\ (1 - R_o) \right] / C_f \qquad (7)$$

$$E_2 = (J_t / J_a)\ (2 - R_o)\ / \left[2 + R_o(J_t - 2) \right] \qquad (8)$$

$$E_3 = (2/R_o)\ (J_t - J_a) / \left[J_a\ (J_t - 2) + J_t \right] \qquad (9)$$

$$E_4 = (C_r - C_f) / \left[R_o(C_r - C_p) \right] \qquad (10)$$

$$F_r = F_f - F_p \qquad (11)$$

$$F_{pc} = F_p \left[1.03{**}(77 - T_f) / 1.8 \right] \quad \text{(Empirical)} \qquad (12)$$

$$GFD = 7.215\ (A \times 10^5) \qquad (13)$$

$$J_a = 1 - 2C_p / (C_f + C_r) = 1 - C_p/C_a \qquad (14)$$

$$J_{fp} = 1 - (J_p/J_f) \quad \text{(Post-Secondary Treatment Area)} \qquad (15)$$

$$J_t = 1 - (C_p/C_f) \qquad (16)$$

$$P_e = \left[(P_f + P_r) / 2 \right] - P_o \qquad (17)$$

$$P_o = 0.008 \left[(C_f + C_r)/2 - C_p \right] \quad \text{(Empirical, based on conductivity data)} \tag{18}$$

$$R_c = F_{pc} / F_f \tag{19}$$

$$R_o = F_p / F_f \tag{20}$$

$$r = \sum xy \Big/ \left(\sum x^2 \sum y^2 \right)^{\frac{1}{2}} = b \Big/ \left[(n - 2) s_b + b^2 \right]^{\frac{1}{2}} \tag{21}$$

$${s_b}^2 = \left[\sum y^2 - \left(\sum xy \right)^2 / \sum x^2 \right] \Big/ \left[(n - 2) \sum x^2 \right] \tag{22}$$

$${s_z}^2 = \left[\sum Z^2 - \left(\sum Z \right)^2 / n \right] / (n - 1) \tag{23}$$

$$\sum x^2 = \sum X^2 - \left(\sum X \right)^2 / n \tag{24}$$

$$\sum y^2 = \sum Y^2 - \left(\sum Y \right)^2 / n \tag{25}$$

$$\sum xy = \sum XY - \left(\sum X \right) \left(\sum Y \right) / n \tag{26}$$

Conversion Factors

Multiply	By	To Get
Gal./min	6.308×10^{1}	Cu cm/sec
Gal./sq ft-day	4.716×10^{-5}	Gm/sq cm-sec
Gal./sq ft-day	6.944×10^{-4}	Gal./sq ft-min
Gal./sq ft-day-psi	6.930×10^{-4}	Gm/sq cm-sec-atm
Gal./sq ft-min-psi	0.9979	Gm/sq cm-sec-atm
Gm/sq cm-sec-atm	1.0021	Gal./sq ft-min-psi
Gm/sq cm-sec-atm	7.2150×10^{5}	Gal./sq ft-day (at 500 psi)
Psi	6.805×10^{-2}	Atmospheres
Sq ft	9.2903×10^{2}	Sq cm

Derivation of Equations

B - Equation (4) :

The solute permeability "constant" is the ratio of the rate of migration of an impurity through a membrane, in mg/sec-sq cm, to the concentration difference across the membrane. In this form it is expressed in cm/sec. The word "constant" is placed in quotation marks to indicate that, when derived as stated, it is only an occasionally useful, easily calculated, yet variable index because it does not take the net operating pressure of the feed flow concentrations into consideration. The same comment would apply, in some small degree, to the A values derived in this report.

From the above definition

$$B = \frac{C_p F_p \,(6.308 \times 10^1)}{M(9.2903 \times 10^2) \;\; (C_f + C_r) \;\; /2 - C_p}$$

After substituting Equations (1) and (14) we obtain

$$B = A\,P_e \times 6.707 \times 10^{-2} \;\; (1 - J_a)\;/J_a \qquad (4)$$

D - Equation (6):

It is frequently desirable to estimate the optimum time between successive membrane cleansings. To do this make the following assumptions:

1. The rate of product flow decreases linearly with time during the relatively short time intervals under consideration;
2. This decrease is due to fouling and not compaction or process changes;
3. The total down time from the start to the finish of the cleansing operation is ninety minutes.

Using the following special notation:

G = Product flow at start of observation period (gal./min)

g = Product dlow one day later (gal./min)

$\tan a$ = $g - G$ (negative) (gal./min-day)

G_a = Average product flow rate during optimum length run (gal./min)

t = Down time as a result of cleansing (min)

T = Optimum running time between cleansing cycles (days)

Then assuming $t = 90$ minutes

$$G_a = \left[1440TG + 1440\ T^2 (g-G)/2\right] /(1440T + 90)$$

Equating first derivative (dG_a/dT) to zero

$$720\ (g-G)\ T^2 + Tt(g-G) + tG = 0$$

Solving

$$T = -0.0625 \left\{1 - \left[1 - 32G/(g-G)\right]^{\frac{1}{2}}\right\}$$

And using standard nomenclature

$$D = -0.0625 \left[1 - (1 + 32G/F_d)^{\frac{1}{2}}\right] \qquad (6)$$

E - Equation (7)

The material balance states

$C_f = C_pR_o + C_r\ (1 - R_o)$, giving

$$E = \left[C_pR_o + C_r\ (1 - R_o)\right] /C_f \qquad (7)$$

E_2 - Equation (8)

$C_f = C_pR_o + C_r\ (1 - R_o)$, or

$C_r = (C_f - C_pR_o)/\ (1 - R_o)$

Then from Equation (14)

$$
\begin{aligned}
1 - J_a &= 2C_p \,/\, (C_f + C_r) \\
&= 2C_p \,/\left[C_f + (C_f - C_pR_o) \,/\, (1 - R_o)\right] \\
&= 2C_p \,(1 - R_o) \,/\left[C_f(1 - R_o) + C_f - C_pR_o\right] \\
&= 2C_p \,(1 - R_o) \,/\left[C_f(2 - R_o) - (C_fC_pR_o) \,/C_f\right]
\end{aligned}
$$

Substituting Equation (16) and rearranging

$$
\begin{aligned}
1 - J_a &= \left[2(1 - J_t)\,(1 - R_o)\right] /(2 - 2R_o + J_tR_o) \\
&= \left[2(1 - J_t)\,(1 - R_o)\right] / \left[2 - R_o(2 - Jt)\right], \text{ and} \\
J_a &= J_t(2 - R_o)/ \left[2 + R_o(J_t - 2)\right] \text{ to give} \\
E_2 &= (J_t/J_a)\,(2 - R_o)\,/\,\left[2 + R_o\,(J_t - 2)\right] \qquad (8)
\end{aligned}
$$

E_3 - Equation (9)

E_3 is developed from Equation (8) by noting

$$R_o \left[J_a\,(J_t - 2) + J_t\right] = 2(J_t - J_a), \text{ and}$$

$$(2/R_o)\,(J_t - J_a) + J_a\,(J_t - 2) + J_t, \text{ hence}$$

$$E_3 = (2/R_o0 \;\; (J_t - J_a)/ \left[J_a(J_t - 2) + J_t\right] \qquad (9)$$

E_4 - Equation (10)

Since $C_pR_o - C_rR_o = C_f - C_r$, therefore

$$E_4 = (C_r - C_f)\,/\left[R_o\,(C_r - C_p)\right] \qquad (10)$$

r - Equation (21)

By definition

$$r = \sum xy / \left(\sum x^2 \sum y^2\right)^{\frac{1}{2}} = (bb_1)^{\frac{1}{2}}$$

$$s_b^2 = \frac{\sum y^2}{(n-2)\sum x^2} - \frac{b^2}{(n-2)}$$ = std. deviation of b

$$b = \sum xy / \sum x^2$$ = log-log slope

$$b_1 = \sum xy / \sum y^2$$

Then $\sum y^2 = (n-2)\sum x^2 \left(s_b^2 + \frac{b^2}{n-2} \right)$

$$= \sum x^2 \left[(n-2)\, s_b^2 + b^2 \right]$$

$$\sum x^2 / \sum y^2 = 1 / \left[(n-2)\, s_b^2 + b^2 \right]$$

And $bb_1 = r^2$

$$b_1/b = \sum x^2 / \sum y^2$$

$$b_1 = b\left(\sum x^2 / \sum y^2 \right)$$

$$r^2 = b^2\left(\sum x^2 / \sum y^2 \right) = b^2 / \left[(n-2)\, s_b^2 + b^2 \right] \qquad (21)$$

APPENDIX SECTION A-2

DAILY RECORD OF FEED pH'S

(OMITTED, See Page 187)

APPENDIX SECTION, A-3

REJUVENATION DATA, AEROJET MEMBRANE SET 1

WEEK	TYPE CLEAN	OZ./GAL.	OZ. WT. USED	pH	PRODUCT GPM		PRESSURE PSI		CONTACT TIME	
					PRE	POST	PRE	POST	SOAK	RECIR.
8	Biz	1	50	8	2.15	3.40	500	610	15 min.	No
10	Biz	1	38	8	2.10	2.55	510	500	15 min.	No
11	Biz	1	38	8	2.25	2.60	520	520	20 min.	No

REJUVENATION DATA, RAYPAK MEMBRANE SET

WEEK	TYPE CLEAN	OZ./GAL.	OZ. WT. USED	pH	PRODUCT GPM		PRESSURE PSI		CONTACT TIME	
					PRE	POST	PRE	POST	SOAK	RECIR.
62	Colo. H_2O			7±						
63	Biz	2	76	9.5	.24	.90	697.5	744	30 min.	
64	Biz	2	76	10.5	.75	1.12	753.5	674.5	33 min.	
64	Biz	2	76	10.5	.78	.76	725	766	35 min.	
64	Biz	2	114	10.5	.29	.61	732.5	725	30 min.	
65	Biz	2	76	10.5	.23	.45	790	797.5	50 min.	
65	NaCOL/Biz	60/2	.4gal/76	10.2	.27	1.10	805	717.5	40 min.	
66	NaOCl	60	.25/gal		.18	.34	836	742.5	15/15/45 min.	
66										
67	Biz/CL_2									
67	Cl_2/pH/Biz/H_2O									
68	CL_2/Biz					.60				

REJUVENATION DATA, AMERICAN STANDARD MEMBRANE SET 1

WEEK	TYPE CLEAN	OZ./GAL.	OZ. WT. USED	pH	PRODUCT GPM		PRESSURE PSI		CONTACT TIME	
					PRE	POST	PRE	POST	SOAK	RECIR.
17	Biz	1	76	6.5						
18	Biz	1	76	7.0						45 min.
19	Biz	1½	76	7.0	5.75	6.05	(720)	(530)		45 min.
21	Biz	1	38	7.5	5.80	6.50	(660)	(640)	Yes	45 min.
23	Biz	1	76	8.0						
26	EDTA	4	200	5.5	5.85	7.15	430	487.5	Yes	60 min.
27	Biz	1	108	8.0	6.45	6.75	535	490	No	50 min.
31	Biz	1	108	7.5	6.40	6.75	565	555	No	45 min.
34	Biz	1	108	7.5	5.00	5.15	640	600	No	65 min.
39	Biz	1	76	7.5	4.70					
42	Biz									
47	EDTA									

SET 2

WEEK	TYPE CLEAN	OZ./GAL.	OZ. WT. USED	pH	PRODUCT GPM		PRESSURE PSI		CONTACT TIME	
					PRE	POST	PRE	POST	SOAK	RECIR.
9	Biz	1	114	8	6.80	7.42	500	492.5		
10	Biz	1	114	8	6.59	6.74	512.5	495		
10	H_2O	-	-	3-5	5.44	5.65	501	510		
10	H_2O	-	-	2.8-5.8	-	-	-	-		
10	H_2O	-	-	3-5	-	-	-	-		
11	Biz	1.5	152	8.5-7.5	5.72	-	497.5	-		
12	Biz			8						
12	Biz	1.5	152	8						
13	Biz	2.5	114	8.5						
14	Biz	2.3	114							
15	Biz	2.3	114							
15	Biz	2.3	114							

REJUVENATION DATA, DU PONT

MEMBRANE SET IA (2 B-5'S IN SERIES, 1 AND 2)

WEEK	PERMEATOR 1 or 2	TYPE CLEAN	OZ./GAL.	OZ. WT. USED	pH	PRODUCT GPM		PRESSURE PSI		CONTACT TIME	
						PRE	POST	PRE	POST	SOAK	RECIR.
7	1	Biz	2	100	10±	5.25		620			
7	1						5.80		620		yes
7	1	Biz	2	100	10±	5.85		620			
7	1						6.40		620		
8	1	Biz	2	100	10±	6.30		610			
8	1						6.90		610		
9	1	Biz	4	228	10±	6.40		615			
9	1						6.65				
14	1	Biz	4	228	10±	6.05					
14	1										
14	1	Inject Chemical "X"					5.55				
14	2	Biz	2	114	10±	.6.05					
14	2						5.55				
14	2	Inject Chemical "X"									
15	2	Biz	4	228	10±	5.35		665		yes	yes
15	2						5.35		630		
16	2	Biz	4	228	10±	5.40		660		no	24 hr.
16	2						5.20		630		
16	2	Biz	2	76	5.2	5.70		645			24 hr.
16	2						5.55		635		
18	2	Vel	½	24	5.0	.85	No Improvement				
						4.85					
18	2	Vel	1		2.0	.85	No Improvement				
18	2	HCL Dilute			2.0		No Improvement				
19	2	Biz		456			No Improvement				
	RENEWED # 2 PERMEATOR (SET # 1 MOD.)										
20	1	Biz	2	76	10±	6.70	7.15	650	625		90 min.
21	1	Biz	2	38	10±	6.45	6.95	660	650	90 min.	
21	2	Biz	2	76	10±	2.10	2.34	660	635	10 min.	5 hr.
21	2					6.50	6.86	660	635		
22	2	Biz	2	76	10±	2.10	NA				
						6.62	6.65				
25	2	EDTA	3.2	5 lbs.	11±	1.69	1.93	635	625		2 hr.
						6.10	6.45				
26	2	EDTA	1.6	5 lbs.	7	1.69	1.90	645	625	2 hr.	1½ hr.
						5.95	6.40				
27	2	EDTA	3.2	10 lbs.	7	6.80	2.05	650	630	1½ hr.	40 min.
						6.32	6.77				
28	2	Biz	2	76	10±	1.76	1.89	630	650	1 hr.	1 hr.
						6.24	6.64				
29	2	EDTA	4	12.5 lbs.	7	1.77	1.82	665		2 hr.	1 hr.
29	2	EDTA	4	12.5 lbs.	7	6.21	6.22		610		

SET IA (cont)

WEEK	SET 1 or 2	TYPE CLEAN	OZ./GAL.	OZ. WT. USED	pH	PRODUCT GPM		PRESSURE PSI		CONTACT TIME	
						PRE	POST	PRE	POST	SOAK	RECIR.
32	2	EDTA	4	12.5 lbs.	7	1.59 6.26	1.65 5.81	660	650		3 hr.
34	1	Biz	2	76							
35	2	EDTA	4	12.5 lbs.	7	1.48 5.40	1.56 5.56				

REJUVENATION DATA, DU PONT MEMBRANE SET IIA

(3-2 PATTERN B-9'S)

WEEK	STAGE 1 or 2	TYPE CLEAN	OZ./GAL.	OZ. WT. USED	pH	PRODUCT GPM		PRESSURE PSI	
						PRE	POST	PRE	POST
39	1	Biz	4	152	10±	5.17	5.22	405	400
39	2	EDTA	4	128	7.5	3.13	3.13	380	377
41	1	Biz	4	152	10±	4.09	4.07	405	412
41	2	EDTA	4	184	7.0	2.60	2.58	375	388
45	1	Biz	4	152	10±		3.20	395	395
45	2	EDTA	4	184	7.0		2.20	360	
49	1	Biz	4	152	10±	3.23		425	400
49	2	EDTA	4	184	7.0	1.81		325	355
50	1	Biz	4	152	10±	3.17	3.56	425	390
50	2	EDTA	4	184	7.0	1.81	2.15	345	355
50	1	Biz	4	152	10±	3.18		420	410
50	2	EDTA	4	128	7.0	1.76			
52	1	Biz	4	152	10±	2.93	3.01	400	400
52		EDTA	4	184	7.0	1.57	1.98	315	355

MEMBRANE SET IIB

(5 IN PARALLEL, B-9'S)

WEEK	TYPE CLEAN	OZ./GAL.	OZ. WT. USED	pH	PRODUCT GPM		PRESSURE PSI		CONTACT TIME	
					PRE	POST	PRE	POST	SOAK	RECIR.
55	Biz/EDTA	4/4	152/128	10/7	4.50	4.58			63/60	
56	Biz/EDTA	4/4	152/128	10/7	3.98	4.40	386	388.5	95/95	
56	Biz/EDTA	4/4	152/128	10/7	4.13	4.38	404	380	49/70	
57	Biz/EDTA	4/4	152/128	10/7	4.19	4.19	400	372.5	50/63	
58	Biz/EDTA	4/4	152/128	10/7	3.80	3.98	417	367.5	90/40	
58	Biz	4	152	10	3.73	3.94	379	381.9	65	
59	Biz	4	190	10±	3.66	3.68	377.5	370	249	
59									60	
60	Biz	3.2	152	10±	2.90	3.04	377.5	371.9	60	
61	Biz	4	190	10±	2.15	3.15	298.5	378.9	70	
61	Biz-R	4	190	10±	3.00	3.17	400	377.8	60	
62	Biz	4	190	10±	2.62	2.71	377.3	376	60	
62	EDTA	4	200	7	2.70		364.5			
62	Biz	4	152	10½	2.02		296			
63	H_2O	-	-	6±	2.48		403.5			
63	Biz	4	190	10½	-	-	-	-		
63	NaHOH			12.9						
63	Biz	4	190	10½						
64	Biz	4	152	10½						
64	Biz	4	-	10½						
64	Biz	4	-	10½						
64	Biz	4	190	10½						
64	EDTA	4	192	7						
64	Biz	4	190	10½	2.14	1.76	417.5			
64	EDTA	4	200	7	2.00	2.14	403.5	400		
64	Biz									
64	EDTA									
65	H_2O									
65	Formaldahyde									
65	H_2O/Air									
76	EDTA/Air									
66	Sulfamic			3-4						

REJUVENATION DATA, GULF MEMBRANE SETS 1 & 2

WEEK	SET 1 or 2	TYPE CLEAN	OZ./GAL.	OZ. WT. USED	pH	PRODUCT GPM		PRESSURE PSI		CONTACT TIME	
						PRE	POST	PRE	POST	SOAK	RECIR.
3	1	Biz	2	76	7	4.35	6.30	567.5	517.5		
4	1	H_2O			5±	5.00	5.50	602.5	592.5	30 min.	
5	1	H_2O			5±	4.55	4.95	592.5	592.5	30 min.	
5	1	H_2O			5±	4.70	5.25	592.5	592.5	30 min.	
5	1	H_2O			5±	4.90	5.50	610	610	30 min.	
5	1	H_2O			5±	5.10		605		30 min.	
5	1	H_2O			5±	5.10	5.50	605	600	30 min.	
6	1	H_2O			4-5	4.65		597.5		30 min.	
6	1	Biz	2	76	7	4.80	6.00	610	595	40 min.	
6	1	Biz	2	76	7	5.80	6.40	607.5	597.5	40 min.	
7	1	Biz	2	76	7	5.65	6.20	610	595	60 min.	
8	1	Biz	2	76	7	5.60	5.70	597.5		40 min.	
8	1	Biz	2	76	7	5.60	5.90	597.5	592.5		
8	1	H_2O			4-5	5.75	6.15	600		30 min.	
9	1	H_2O			4-5	5.60	5.65	610		30 min.	
9	1	Biz	2	76	7	5.60	5.70	595	595	40 min.	
9	1	H_2O			4-5	5.65	5.90	600		30 min.	
10	1	Biz	2	76	7	5.65	5.85	601.5		40 min.	
11	1	Biz	2	76	7	5.55	5.80	592.5		40 min.	
11	1	Biz	2	76	7	5.65	5.95	600	595	40 min.	
13	1	Biz	2	76	7	5.85	6.15	610	595	30 min.	
14	1	Biz	2	76	7.2	5.80	6.20	612.5	607.5	30 min.	
15	1	Biz	2	76	7.2	5.70	5.95	592.5	597.5	30 min.	
16	1	Biz	2	76	7.6	5.60	6.10	615	597.5	30 min.	
16	1	H_2O				5.50	6.00	600			
17	1	Biz	2	76	7	5.95	6.10	612.5	597.5	30 min.	
18	1	Biz	2	76	7	5.90	6.10	607.5	597.5	30 min.	
19	1	Biz	2	76	7	6.00	6.40	607.5	597.5	30 min.	
23	1	Biz	2	76	7	6.05	6.30	597.5	587.5	45 min.	
26	1	EDTA	4	200	7	5.85	6.30	622.5	587.5	60 min.	
27	1	Biz	2	76	7	6.10		597.5		55 min.	
28	1	EDTA	4	200	7	6.10	6.50	587.5	595.	50 min.	
29	1	Biz	2	76	7.5	5.70	6.10	597.5	607.5	65 min.	
30	1	EDTA	4	200	7	5.80	6.10	620	605	60 min.	
33	1	Biz	2	76	8.5	5.65	5.90	597.5	597.5	50 min.	
35	1	Biz	2	76	8	5.45	5.70	612.5	587.5	60 min.	
35	1	EDTA	4	200	7	5.0	5.35	622.5	597.5	70 min.	
36	1	Biz	2	76	8	4.65	5.10	607.5	598.5	53 min.	
37	1	EDTA	4	200	7±	4.60	4.60	614.5		50 min.	
37	1	Biz/EDTA		76/64	7.5	4.35	4.70	607.5	590	50 min.	
38	1	Biz/EDTA		76/64	7±	4.35	4.70	582.5	590	75 min.	
40	1	Biz/EDTA		76/64	7±	4.03	4.40	587.5	591	53 min.	
41	1	Biz/EDTA		76/64	7	4.10	4.20	611	591	70 min.	
42	1	Biz/EDTA		76/64	8	3.92	4.05	608.5		71 min.	

MEMBRANE REJUVENATION, GULF (cont)

WEEK	SET 1 or 2	TYPE CLEAN	OZ./GAL.	OZ.WT. USED	pH	PRODUCT GPM		PRESSURE PSI		CONTACT TIME	
						PRE	POST	PRE	POST	SOAK	RECIR.
44	1	Biz/EDTA		76/64	7.5	3.77	4.10	597.5		51 min.	
45	1	Biz	2	76	8	3.68	3.98	615	599	78 min.	
46	1	EDTA	4	200	7	3.80	3.95	608	600	72 min.	
46	1	Biz	4	152	7.8	2.95	3.73	630	600	48 min.	
47	1	Biz	2	76	8	2.87	3.77	636.5	603.5	55 min.	
47	1	H_2O			3	3.20	3.20	638.5	591.5	45 min.	
47	1	Biz	2	76	8	2.78	3.47	607	602.5	77 min.	
48	1	Biz	2	76	8	3.25	3.68	605	597.5		
51	2	Biz	2	76	8	4.70	5.78	465	400	50 min.	
51	2	Biz	2	76	8	4.53	5.90	452.5	472.5	45 min.	
52	2	Biz	2	76	8	4.30	5.40	568.5	530	45 min.	
52	2	EDTA	4	160	7	4.76	4.90	557.5	553.5	32 min.	
53	2	Biz	2	76	8	3.72	4.45	539	560	25 min.	
53	2	Biz/EDTA	2/4	76/160	7/7	4.07	4.50	581	577.5	34/40 min.	
53	2	H_2O			3/4	4.45	4.40	606	587.5	58 min.	
54	2	Biz	2	76	7	3.80	4.37	595	580	43 min.	
54	2	H_2O			3/4	4.02	4.07	580	588.5	58 min.	
54	2	Biz	2.3	114	8	3.72	4.15	598.5	585	62 min.	
54	2	Biz	2.3/3.2	266	7	3.83	3.96	595	598.5	79 min.	
55	2	Biz	2.3	114	8	3.42	3.97	590	582.5	62 min.	
55	2	Biz	2.3	114	8	3.65	4.10	600	581.5	72 min.	
55	2	H_2O			2-3	3.85	3.88	592.5	583.5	62 min.	
56	2	Biz	1.5	76	8	3.75	4.25	583.5	570	27 min.	
56	2	H_2O			4	3.75	3.76	577.5	586	36 min.	
56	2	Biz	1.5	76	6	3.77	4.07	587.5	581.5	94 min.	
56	2	H_2O/Biz	/1.5	/76	1.7/8	4.08	4.50	581.5	596	27/29 min.	
56	2	Biz	1.5	76	8	4.08	4.50	592.5	587.5	62 min.	
57	2	Biz	1.5	76	8	3.87	4.45	600	579	71 min.	
57	2	Special		132		3.86	4.18	591	587.5		
58	2	Biz	1.5	76	8	3.72	4.09	597.5	565	45 min.	
58	2	Biz	1.5	76	8	3.87	4.09	588.5	590	39 min.	
58	2	Biz	1.5	76	8	3.69	3.92	597.5	590	45 min.	
59	2	Biz	1.5	76	8	3.19	3.72	593.5	581.5	55 min.	
59	2	Biz	1.5	76	6.8	3.55	3.80	586.5	592.5	51 min.	
59	2	Biz	Plant Shut Down								
60	2	Biz	1.5	76	8	3.37	3.50	585.5	592.5	47 min.	
60	2	Biz	1.5	76	8	3.20	3.68	600	598	60 min.	
61	2	Biz	1.5	76	8	3.20	3.55	590.5	595	60 min.	
61	2	H_2O			2.5	3.26	3.36	624	589	20 min.	
61	2	Biz	1.5	76	8	3.11	3.33	600	592.5	50 min.	
62	2	Biz	2.3	114	8	2.60	2.84	601.5	585	80 min.	
62	2	H_2O			2.5	2.55	2.55	625.5	610.5	30 min.	
62	2	H_2O			2.5	2.21	2.40	615	583.5	30 min.	
62	2	H_2O			5.5	2.10	2.61	571	603.5	30 min.	
63	2	H_2O			2.5	2.00	2.05		568.5	40 min.	
63	2	Biz	3.8	190	8.0	2.04	2.15	575	565	35 min.	

MEMBRANE REJUVENATION, GULF (cont)

WEEK	SET 1 or 2	TYPE CLEAN	OZ./GAL.	OZ. WT. USED	pH	PRODUCT GPM		PRESSURE PSI		CONTACT TIME	
						PRE	POST	PRE	POST	SOAK	RECIR.
63	2	Biz	1.5	76	8	2.00		620.5		80 min.	
63	2	Biz	2.3	114	8	2.03	2.62	603	583.5	80 min.	
64	2	Biz I	2.3	114	8	1.95	2.75	578.5	562.0	90-130 min.	
64	2	Biz I	2.3	114	8			Pump Bad		90-170 min.	
65	2	NaOCL					3.5±	"	"		
OFF FROM 5-18 to 6-3-71											
67	2	Biz-CL	2.3	114	8	1.73	2.70	542.5	570	58-34 min.	
67	2	Biz-I	2.3	114	8	1.98	3.32	557.5	585	57 min.	
67	2	Biz-I	2.3	114	8	2.35	2.87	596	577.5		
68	2	NaOCL	100ml/50gal.			2.09	2.55	585	582	62 min.	

REJUVENATION DATA, UNIVERSAL MEMBRANE SETS 1,2,3,&4

WEEK	SET NO.	TYPE CLEAN	OZ./GAL.	OZ. WT. USED	pH	PRODUCT GPM		PRESSURE PSI		CONTACT TIME	
						PRE	POST	PRE	POST	SOAK	RECIR.
7	1	Biz	2	100	10±	4.75	5.65			no	30 min.
8	1	Biz	2	100	10±	5.15	5.70				
9	1	H_2O				5.60	5.70				
9	1	H_2O				5.90	5.90				
10	1	H_2O				5.70					
10	1	Biz	2	114	10±	5.45	5.95				
10	1	H_2O				5.55					
10	1	H_2O				5.95					
11	1	H_2O									
11	1	H_2O									
11	1	H_2O				5.85					
11	1	Biz	2	114	10±	5.75	6.25				
13	1	Biz	2	114	10	5.95					
15	1	Biz	2	114	10±	5.20	5.70	582	570		20 min.
22	1	Biz	2	72	10±	5.75		5.25			60 min.
23	1	Biz	2	72	10±	5.60	8.10	502	460		50 min.
23	2	Biz	2	76	10	5.60	8.10	502	460		50 min.
24	2	Biz	2	76	10	5.50	7.45	502.5	472.7		60 min.
25	2	Biz	2	76	10	5.45	6.65	505	480		60 min.
26	2	Biz	2	76	10	5.60	6.60	502.5	480		75 min.
26	2	H_2O	2			5.70	5.75				30 min.
27	2	Biz	2	76	10	5.10	5.50	515	497.5		40 min.
27	2	Biz	2	76	10	5.10	5.65	500	560		55 min.
27	2	Biz	2	76	10	4.35	4.55	585	560		55 min.
28	2	EDTA	2	76	10	4.35	4.25	630	587.5		55 min.
28	2	Biz	2	76	10	3.80	3.80	605	620		75 min.
29	2	Biz	2	76	10	3.30	3.20	635			60 min.
29	2	Biz	1	38	10	3.15	3.30	590	595		30 min.
30	2	Biz	2	76	10	2.55	3.05	590	632.5		55 min.
32	REMOVED MODULES										
33	3	Biz	2	76	10±	2.45	2.80	527.5	507.5		50 min.
34	3	Biz	2	76	10±	2.40	2.20	550	480		60 min.
37	3	Biz	2	76	10±	2.44	2.57	555	515		65 min.
39	3	Biz	2	76	10±	2.08	2.25	505	492.5		75 min.
41	3	Biz	2	76	10±	2.17	2.43	507.5	515		63 min.
45	3	Biz	4	152	8±	1.90	2.11	560	572.5		41 min.

MEMBRANE REJUVENATION, UNIVERSAL (cont)

WEEK	SET NO.	TYPE CLEAN	OZ./GAL.	OZ. WT. USED	pH	PRODUCT GPM		PRESSURE PSI		CONTACT TIME	
						PRE	POST	PRE	POST	SOAK	RECIR.
51	4	Biz	2.3	114	8	3.05	4.45	560	522.5		40 min.
51	4	Biz	2.3	114	8	3.48	5.10	545.	540		45 min.
52	4	Biz	2	76	8	3.37	3.95	572.5	562.5		35 min.
52	4	Biz	2.3	114	7.5	3.97	4.47	570	537.5		45 min.
53	4	Biz	2.3	114	8	3.40	3.98	560	540		33 min.
53	4	Biz	2.3	114	8	3.77	4.30	552.5	552.5		36 min.
54	4	H_2O			5	3.88	4.05	572.5	550		40 min.
54	4	Biz	2.3	114	8.5	3.75	4.20	562.5	555		48 min.
54	4	H_2O			4-5	4.05	4.07	550	545		40 min.
54	4	Biz	2.3	114	8±	3.87	4.50	551.5	562.5		48 min.
55	4	Biz	2.3	114	8±	4.15	4.57	585	565		52 min.
55	4	Biz	2.3	114	8±	4.17	4.55	567.5	550		63 min.
56	4	Biz	2.3	114	8±	4.45	4.52	550	540		30 min.
57	4	Biz	2.3	114	7.8	3.98	4.50	550	545		40 min.
58	4	Biz	1.5	76	8.2	4,08	4.66	570	550		70 min.
59	Main Plant Off										
60	4	Biz	1.5	76	8	3.69	4.30	527.5	538		70 min.
62	4	Biz	1.5	76	7.4	3.11	3.48	549	539		
62	4	H_2O			2.75						
63	4	Biz	1.5	76	7.5			551			73 min.
63	4	Biz	2.3	114	8.5	2.65	3.92	582.5			85 min.
64	4	Biz	2.3	228	8.5						65 min.
65	4	Biz									
66	4	Biz									
67	4	Biz	2.3	114	8.8	3.10					
67	4	Biz	2.3	114	8.6						
68	4	Biz									

APPENDIX SECTION A-4

FEED TREATMENT PROCESS REJUVENATIONAL RECORD

SAND FILTERS (S-1, S-2, S-3) BACKFLUSH HISTORY

WEEK NO.	UNIT	DURATION (MINUTES)	VOLUME (GALLONS)	PRESSURE DIFFERENTIAL		FLOW CONFIGURATION
				PRE BACKFLUSH	POST BACKFLUSH	
2	S-2	15'	2150	14	3	Single
3	S-3	-	2800	18	1	Single
5	S-1	15'	1700	17	1	Single
6	S-2	15'	1600	6	0	3 in Parallel
8	S-3	15'	1600	14	0	" " "
10	S-1	10'	1300	8	0	" " "
10	S-2	9'	1100	7	0	" " "
10	S-3	10'	1000	8	0	" " "
13	S-1	20'	3000	16	0	" " "
13	S-2	25'	2600	16	0	" " "
13	S-3	20'	2600	17	0	" " "
15	S-1	15'	2700	14	0	" " "
15	S-2	15'	3100	13	0	" " "
15	S-3	15'	2300	15	0	" " "
17	S-1	15'	2400	19	0	" " "
17	S-2	15'	1800	17	0	" " "
17	S-3	15'	2600	9	0	" " "
20	S-1	-	3000	20	0	" " "
20	S-2	-	3000	20	0	" " "
20	S-3	-	3000	20	0	" " "
22	S-1	20'	3000	15	0	" " "
22	S-2	13'	2000	15	0	" " "
22	S-3	17'	3000	15	0	" " "
24	S-1	18'	3000	15	4	" " "
24	S-2	18'	3000	15	2	" " "
24	S-3	21'	3000	15	0	" " "
26	S-1	19'	3100	17	0	" " "
26	S-2	18'	3000	17	0	" " "
26	S-3	50'	3150	17	0	" " "
28	S-1	17'	3000	20	0	" " "
28	S-2	19'	3000	20	0	" " "
28	S-3	19'	3000	20	0	" " "
30	S-1	14'	1500	6	1	" " "
30	S-2	10'	1500	6	1	" " "
30	S-3	10'	1900	6	1	" " "
35	S-1	15'	1800	18	7	" " "
35	S-2	11'	1800	18	7	" " "
35	S-3	10'	1650	18	7	" " "

SAND FILTERS (S-1, S-2, S-3) BACKFLUSH HISTORY

WEEK NO.	UNIT	DURATION (MINUTES)	VOLUME (GALLONS)	PRESSURE DIFFERENTIAL		FLOW CONFIGURATION
				PRE BACKFLUSH	POST BACKFLUSH	
41	S-1	17'	3000	24	0	3 in Parallel
41	S-2	18'	3000	24	0	" " "
41	S-3	21'	3400	24	0	" " "
44	S-1	22'	3900	14	0	" " "
44	S-2	22'	5500	14	0	" " "
49	S-1	20'	3000	10	0	" " "
49	S-2	20'	3000	10	0	" " "
49	S-3	20'	3000	10	0	" " "
49	S-1	-	4000	6	0	" " "
49	S-2	-	4000	6	0	" " "
49	S-3	-	5700	10	0	" " "
51	S-1	18'	3000	16	0	" " "
51	S-2	18'	3000	16	0	" " "
51	S-3	22	3000	16	0	" " "
52	S-1	20'	3100	9	0	" " "
52	S-2	17'	3000	9	0	" " "
52	S-3	20'	3000	9	0	" " "
53	S-1	20'	2900	8	0	" " "
53	S-2	20'	3000	8	0	" " "
53	S-3	20'	3000	8	0	" " "
54	S-1	20'	2500	10	0	" " "
54	S-2	19'	2400	10	0	" " "
54	S-3	19'	2400	10	0	" " "
55	S-3	60'	10000	0	0	" " "
55	S-1	25'	4800	13	0	" " "
55	S-2	25'	4800	13	0	" " "
55	S-3	11'	900	13	0	" " "
56	S-1	20'	3000	5	0	" " "
56	S-2	17'	3000	5	0	" " "
56	S-3	18'	3000	5	0	" " "
57	S-1	23'	3500	8	0	" " "
57	S-2	25'	3500	8	0	" " "
57	S-3	24'	3500	8	0	" " "
58	S-1	11'	1000	7	0	" " "
58	S-2	9'	800	7	0	" " "
58	S-3	11'	1000	7	0	" " "
58	S-1	27'	3500	6	0	" " "
58	S-2	27'	3800	6	0	" " "
58	S-3	27'	3500	6	0	" " "
59	S-1	32'	3500	18	1	" " "
59	S-2	33'	3500	18	1	" " "
59	S-3	34'	3500	18	1	" " "

SAND FILTERS (S-1, S-2, S-3) BACKFLUSH HISTORY

WEEK NO.	UNIT	DURATION (MINUTES)	VOLUME (GALLONS)	PRESSURE DIFFERENTIAL		FLOW CONFIGURATION
				PRE BACKFLUSH	POST BACKFLUSH	
59	S-1	-	3000	-	-	3 in Parallel
59	S-2	-	3000	-	-	" " "
59	S-3	-	3000	-	-	" " "
60	S-1	27	3000	11	0	" " "
60	S-2	28	3000	11	0	" " "
60	S-3	27	3000	11	0	" " "
61	S-1	-	3500	17	2	" " "
61	S-2	-	3300	17	2	" " "
61	S-3	-	3700	17	2	" " "
62	S-1	-	2600	15	9	" " "
62	S-2	-	3200	15	9	" " "
62	S-3	-	3200	15	9	" " "
62	S-1	-	6200	9	3	" " "
62	S-2	-	4000	9	3	" " "
62	S-3	-	3500	9	3	" " "
62	S-1	-	4000	6	0	" " "
62	S-2	-	3700	6	0	" " "
62	S-3	-	3600	6	0	" " "
63	S-1	40'	4000	2	0	" " "
63	S-2	40'	4700	2	0	" " "
63	S-3	40'	4500	2	0	" " "
63	S-1	33'	4300	3	0	" " "
63	S-2	33'	4300	3	0	" " "
63	S-3	36'	4300	3	0	" " "
63	S-1	30'	4200	4	0	" " "
63	S-2	33'	4200	4	0	" " "
63	S-3	32'	3200	4	0	" " "
64	S-1	30'	4200	3	0	" " "
64	S-2	30'	4200	3	0	" " "
64	S-3	30'	4200	3	0	" " "

CARBON FILTERS (C-1, C-2, C-3) BACKFLUSH HISTORY

WEEK NO.	UNIT	DURATION (MINUTES)	VOLUME (GALLONS)	PRESSURE DIFFERENTIAL		FLOW CONFIGURATION
				PRE BACKFLUSH	POST BACKFLUSH	
5	C-2	60'	3200	11	1	Single
6	C-1	40'	2800	12	0	C-1,C-2,C-3 Series
6	C-2	40'	3450	1	0	"
6	C-3	45'	2950	3	0	"
7	C-2	15'	2800	4	0	"
7	C-3	10'	1400	5	0	"
12	C-1	60'	9400	4	2	"
13	C-2	40'	6300	3	0	"
13	C-3	45'	7900	3	1	"
16	C-1	120'	12400	10	1	"
22	C-1	30'	7900	14	0	"
27	C-1	60'	5250	29	0	"
30	C-1	50'	7000	22	0	"
37	C-1	60'	8750	16	0	"
39	C-1	60'	9600	28	1	"
42	C-1	55'	9400	23	0	"
44	C-2	65'	9500	14	1	"
48	C-1	-	-	9	-	"
48	C-2	-	-	12	-	"
48	C-3	-	-	2	-	"

D. E. FILTERS (D-1, D-2) PRECOAT RECHARGE HISTORY

WEEK NO.	UNIT	DURATION (MINUTES)	VOLUME (GALLONS)	PRESSURE DIFFERENTIAL		CONDITION CONFIGURATION
				PRE BACKFLUSH	POST BACKFLUSH	
7	D-1	15'	5300			Pre-Coating Each Time
7	D-2	10'	2000			" "
13	D-1	63'	1300	22	17	" "
13	D-2	63'	1300	24	17	" "
13	D-1	75'	2800	20	0	" "
13	D-2	40'	1300	22	5	" "
15	D-1	-	1900	-	2	" "
15	D-2	-	3500	-	1	" "
17	D-1	-	1400	-	-	" "
17	D-2	-	1500	-	-	" "
19	D-1	15'	2000	16	1	" "
19	D-2	15'	2000	16	1	" "
20	D-1	5'	2000	9	3	" "
20	D-2	5'	2000	10	4	" "
21	D-1	15'	1300	3	3	" "
21	D-2	15'	1300	4	4	" "
23	D-1	35'	1600	3	3	" "
23	D-2	67'	2300	3	3	" "
24	D-1	35'	1300	47	10	" "
24	D-2	35'	1300	47	10	" "
30	D-1	60'	11000	4	3	Single
30	D-1	-	-	2	-	"
30	D-2	-	-	2	-	"

APPENDIX SECTION, A-5

COMMENTS ON NITRATE AND PHOSPHATE ANALYSES

Introduction

Nitrate concentrations have proven to be the most variable of the common analytical determinations used to monitor the results of wastewater treatment and the various tertiary treatments, including reverse osmosis, encountered in this project.

The newly issued 13th Edition of Standard Methods listing five "Tentative" methods for nitrates in polluted waters, concedes the difficulties involved and though avoiding a specific selection lists enough precision and accuracy data to stress the likelihood of wide variations in duplicates, especially at concentrations below one mg/l NO_3-N.

A Brucine Method similar to that in the 1969 FWQA Manual was used in this work and is one of the "Tentative Standard Methods". Organic matter in high concentrations is listed as a probable interference. It was concluded from experimental results on this project, that both the organic suspended solids and the dissolved organics usually present in secondary effluent are important interferences in the brucine nitrate analysis. Discussions with others indicated that extreme efforts, such as walk-in refrigerator titrations, have been employed to improve the precision of the analyses. The potential use of nitrate analyses for process plant control or pilot plant development comparisons make it desirable to have a more economical, faster, and precise (that is, more reproducible) analysis, even perhaps at the expense of less absolute accuracy. An attempt was made to satisfy that need by carefully studying results on standards, regular and spiked samples.

Theory

The deviation within brucine nitrate analyses seems to include:
(a) an absolute deviation independent of the sample and
(b) a variable deviation dependent upon sample interferences

The magniture of the absolute deviation depends not only upon the photometric equipment and analytical technique but also on extreme care in precise duplication of reaction times and temperatures.

In typical wastewater samples the variable deviation appears to be a combination of a fixed first order function of the measured absorbance, plus a second order function of the sample size. The first, when multiplied as a constant by the concentration, is a direct percentage variable, independent of the original sample size, and per se should not influence the choice of sample concentration. It gives the least percentage error with the largest sample, and it therefore encourages use of undiluted samples. The second order function probably represents a reaction between the nitrate and the interference, in which (Absorbance)equals (NO_3) X (Interference) or a (sample size) X b (sample size) or ab (sample size squared). This gives the greatest variation, both absolute and percentage-wise, with the most concentrated sample, and thus encourages use of the maximum dilution. It is suggested that this second order function represents more error than deviation, that is, it is consistently high (or low) depending upon the nature of the interference, and yields good precision though less accuracy, and poorer spike recoveries, when large numbers of samples are averaged.

This may explain why some analysts prefer the maximum practical dilution to obtain accuracy even at the expense of higher labor costs (or fewer analyses) and less precision. It is believed that the aspects of both cost and precision justify the adoption of the simpler procedure (with experimental corrections which can reduce the errors below those due to normal deviations of the standard method) for repeated analyses of the same process streams - as in process control or development studies.

It would be a substantial improvement if duplicates could agree within ten per cent instead of the twenty-five per cent common by standard methods.

Experimental Results

Uniformly good precision was attained with a simplified procedure relative to previously published variations of the brucine nitrate method. It is still necessary, however, to use "grab samples" obtained at the same time from the feed, product and brine of the reverse osmosis units in order to obtain the desired agreement on material balances.

Samples spiked with secondary effluent or its concentrated brines gave low results (averaging about 90% agreement). Filtration of secondary effluent and brine samples gave poorer factors, suggesting that a positive error from the suspended solids was partly offsetting the negative error from the dissolved solids in the wastewater effluent. Filtration therefore did not justify the extra time and labor involved, since it merely gave a less accurate answer.

A brief experiment with an activated carbon preliminary separation, virtually eliminated the nitrate detectible by the proposed method which explains the reduction in nitrate between post-reactor-clarifier samples and post-carbon samples during post-secondary treatment. The latter effect may disappear upon "nitrate saturation" of the carbon, but this aspect was not investigated. Preliminary separation with chloroform, which has been recommended as a stabilizing agent for nitrate samples, showed some promise for improved accuracy but at the expense of greater deviation (probably due to the residual chloroform). However, a countercurrent chloroform extraction followed by a "kerosene" extraction might improve accuracy though at the expense of a higher labor cost.

The major interference appeared to be organic material, both dissolved and suspended, and the results suggest that there was a "minimum" percent agreement of nitrate versus organic interference concentration, so that the positive and negative errors were partially offsetting, but were not affecting results by the same slope of absorbance curve of concentration. As a statement of observation, the lower the nitrate concentration (such as in the products) the greater the correction needed; the greater the nitrate concentrations (brines with high interference character) the less need for correction.

Procedure

The proposed method is extremely simple, though it requires the typical safety precautions due any Brucine Method. Since the sample is diluted less, extra care is recommended in adding concentrated sulfuric acid. Tubes must always be pointed away from the face and instruments when shaking. The sample plus reagent mixing is accomplished in a "matched set" of "test tubes" suitable for the spectro-photometer used. The following procedures, which may be modified to suit available equipment, is recommended:

A. For One Inch Diameter Photometer "Test Tubes":
   1. Pipet five ml sample into one inch diameter test tube in a suitable rack
   2. Add ten ml of acidified brucine reagent rapidly from a Fisher automatic pipet
   3. Promptly shake or vibrate the tube for ten seconds. A combined swirling and tapping motion is effective. The next tube may be filling while the first is being mixed
   4. About ten minutes should be allowed for cooling. Readings may be taken on a suitable photometer (The Bausch and Lomb Spectronic 20 was used in Hemet) whenever convenient during the next three days.
   5. A blank is needed to set the photometer at 100% transmittance, and at least one standard should be read with each group of samples. (The curve is not straight; at least four standards should be used to plot the shape. The number of standards and the frequency of their use depend upon the precision required.) The nitrate concentration is read from the graph. The answer is obtained by multiplying by the appropriate dilution and correction factors.

B. For Half Inch Diameter Tubes:
   1. Pipet one ml of sample into a half-inch diameter test tube in a suitable rack
   2. Squirt two (2.0) ml of acidified brucine reagent rapidly into the sample from a marked measuring autopipet
   3. Shake the tube for ten seconds by tapping sharply against a gloved finger
   4 and 5. Same as for larger tubes

C. Dilutions:
   For the five ml samples, with one inch diameter tubes, dilutions are easily made by pipetting in one to five ml of sample, then adding the remaining distilled water needed for the five ml total

from a 50 ml reservoir buret. (If greater dilutions are needed, add the water first and rinse the micropipet in the diluted sample twice. Separate dilutions are satisfactory if preferred.)

D. Acidified Brucine Reagent:
The brucine reagent and the sodium arsenite solution, as described in both Standard Methods and the "FWQA Manual", are mixed with concentrated sulfuric acid with cooling to minimize reactions. This mixed reagent gradually turns yellowish, even when refrigerated. Setting the blank at 100% corrects partially for these reagent color changes, but does not correct for the slight shift of the standards curve. The useful life of the reagent may be monitored by checking the blank against distilled water set at 100%, and changing at some selected level, such as 80% transmittance of blank versus water at 100%. (The specific percentage chosen will depend upon the precision required and the number of samples to be analyzed.)

In order to minimize heating and extend the useful life of the mixture, the acid was cooled and the other reagents added in several increments with intermediate cooling. Specifically, 2½ ml sodium arsenite was added by pipet at the bottom of a 500 ml graduate of sulfuric acid, which was then covered and chilled in the freezing compartment of a refrigerator. Then 10 ml of brucine was added by pipet, near the bottom, slowly, stirring with the pipet. After chilling again, twenty ml of brucine was added, and another chilling preceded the final 20 ml addition. After thorough mixing, the acidified reagent is ready for use.

E. Range of Method:
Whereas the FWQA method suggests a range of 0.1 to 2.0 mg/l NO_3-N, but is only reasonably precise between 1 mg/l and 2 mg/l NO_3-N, this method is convenient for a range of 0.5 to 7 mg/l NO_3-N with one inch diameter tubes, or for 1 to 14 mg/l NO_3-N with half inch diameter tubes. Higher concentrations can be used if extra standards are used and special curves and readings taken, setting a medium concentration standard as 100%, and keeping all samples in those runs above that concentration. Thus the entire range in most typical well or wastewater samples may be run without any dilution step. Spiking samples with standards is recommended occasionally to double-check the accuracy.

Summary:

Precise nitrate analyses can be obtained in as simple a procedure as is possible photometrically: "Pipet sample, mix in one reagent, read on photometer, read off graph". Correction factors can improve the accuracy. Standard spikes and different dilutions help to indicate the probable accuracy. Thermal control is provided by the heat of sulfuric acid dilution under repetitive but simple mixing conditions. No heating or cooling baths are required. (Cooling is used in reagent preparation, which can be done weekly.) The average absolute error of individual corrected results on wastewater samples is believed to be lower than by various published Brucine Methods.

Summary Comments on the Phosphate Ascorbic Acid Analysis

The ascorbic acid method is an excellent photometric analytical method. It is quite precise and accurate for waste water analyses. The persulfate digestion is effective but not usually justified on secondary effluent due to biological "digestion" in the activated sludge process. The greatest weaknesses of the method are the high sensitivity to glassware rotation or changes at the high 880 Mμ wavelength, and the short "shelf" life of critical reagents. The mixed reagent should be made fresh daily. The ascorbic acid solution may be made fresh weekly if refrigerated. The ammonium phosphomolybdate is much more sensitive to degradation in this method than in the ANSA method, and must be refrigerated. The curve is very reproducible, and failure of the standards to reach their customary absorbance indicates the possible need for fresh reagents. Whenever this happens, re-reading the samples after sufficient time delay to permit full color development will provide more accurate results. Usually the color will stabilize within three hours and remain relatively stable several days, unless phosphate and total solids concentrations are so high that the dye precipitates. When color development is incomplete, the color development rate varies widely according to temperature, concentration of salts, etc. so that wide differences result between "digested" and "ortho" samples. These differences are eliminated by waiting until the color stabilizes.

APPENDIX SECTION A-6

COMPUTER PRINTOUT SUMMARY

(Omitted, See Page 187)